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**WL-TR-96-2095**

**AERO-THERMAL CASCADE TUNNEL  
FLOW QUALITY: TURBULENCE  
GENERATION AND PREDICTION**



**John Duncan  
Kristin Petersen**

**29 NOVEMBER 1995**

**FINAL REPORT 1 NOVEMBER 1995--9 JULY 1996**

**Approved for public release; distribution unlimited**

**AERO PROPULSION & POWER DIRECTORATE  
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13. ABSTRACT (Maximum 200 words) Turbine blade temperatures in modern turbine engines are the limiting factor in the advancement of aircraft propulsion today. One reason for the blades' thermal stress failure has to do with the traverse effects of turbulent flow over the blades--the more turbulence in the flow, the greater the heat transfer to the blade. Of concern here are both freestream and boundary layer turbulence. Therefore, the focus of much research today is on studying turbine blade models with post-burner turbulent flow conditions in order to design and build blades around the predicted failure levels and coordinates. The focus of this paper is on the generation of the turbulence characteristics which will be necessary for use in cascade wind tunnel facilities. Methods of turbulence generation and turbulence trends are analyzed with the main parameter being turbulence intensity variation with both lateral and streamwise location. The results presented here are a complete turbulent flow field description for a turbulence generation method, supporting the "air off" grid configuration as ready for use and research while demanding revision of the "air on" high turbulence generation method.				
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**Objective:**

This research experimentally characterizes turbulent flow produced with an upstream turbulence generation grid in the USAF Academy Aero-thermal Cascade Facility. A full characterization of flow quality in this case consists of (a) planar velocity and turbulence intensity mapping, and (b) streamwise variations in turbulence intensity and length scales. In application, a desired flow quality, for subsequent turbulent flow heat transfer experiments, can be reproduced based on the computational data trends and tunnel/grid specific flow variations detailed here. Results from the current experiments will also help in the improvement of turbulence grid design and as a comparison for existing turbulent flow CFD codes and equations, such as the linear Roach correlation for turbulence intensity and decay rate.

All flow quality relationships are analyzed with respect to whether or not the grid air jets (pressurized air injected from the from grid points across the freestream flow) are on or off, and using both mean and centerline values where appropriate.

**Background:**

The research done here will contribute to a better knowledge of how to generate and predict turbulence. The conditions researched here, based on Reynolds number similarity ( $Re \approx 10^4$ ), allows direct application of the results in modeling low pressure (3rd-4th stage) turbine blades which are typically around 10-20% turbulence intensity. More importantly, the turbulence is directly related to the heat transfer coefficient of the blades, based on an understanding of basic thermodynamics and quantified by the equation:

$$h = \frac{q}{(T_{srr} - T_{surf})}$$

Heat transfer coefficient,  $h$ , (dependent on  $T_{surf}$ ) changes, however, based on turbulence. The prerequisite, then, is adequate turbulent flow test conditions. Turbulence vortex intensities and their decay rates, and macroscopic length scales will be the main interest in the turbulence characterization. These parameters are the most helpful in visualizing the strength (energy) and size of the eddies present in the flow. Variation in these parameters is dependent primarily on distance from the turbulence

	UCDavis	USAF Academy
Operation	Open Loop	Closed Loop
Axial Chord (Bx)	0.171 m	0.166 m
Blade Pitch (p)	.159 m	.196 m
Pitch/Axial Chord	.93	1.18
Span/Axial Chord	3.56	3.97
Inlet Camber Angle	44°	46.5°
Exit Camber Angle	26°	23.5°
Air Inlet Angle (B <sub>i</sub> )	44.7°	49°
Air Exit Angle (B <sub>e</sub> )	26°	23.5°
Grid	Perpendicular to free-stream	Parallel to cascade
Turbulence (clean.grid)	1% 10%	.5% 9%
Re (clean.grid)	144,000 134,000	110,000 110,000

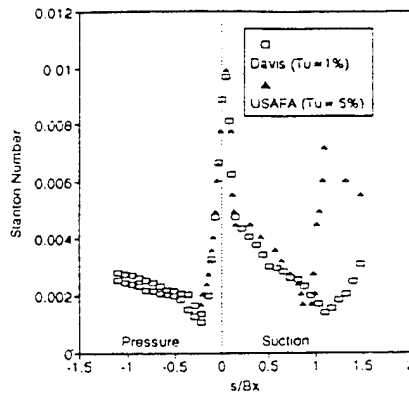


FIGURE 6. UCDAVIS (Re=144K) AND USAFA (Re=110K) RESULTS AT LOW TURBULENCE

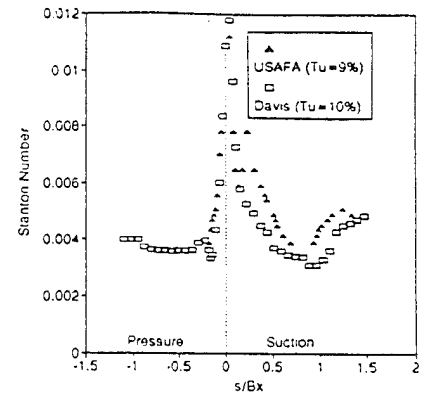


FIGURE 7. UCDAVIS (Re=134K) AND USAFA (Re=110K) RESULTS AT HIGHER TURBULENCE

### Figure 1. USAFA and UCDavis Turbulent Flow Results Comparison

(Taken from Baughn, et al, "An Experimental Investigation of Heat Transfer, Transition, and Separation on Turbine Blades at Low Reynolds Number and High Turbulence Intensity")

Cascade tunnel results have sometimes been scrutinized for the inability of the tunnel to model rotational flow, spanwise flow, and sequential blade array effects characteristic of a rotating turbine spool. However, the analysis done in the above cascade experiments showed that both sets of data compared favorably to actual rotational data (Baughn 13).

#### Expected Results/Theory:

The data collected will allow two things to be done. The first is to characterize turbulent flow at various x,y, and z positions away from the grid. This, in turn, will allow predictions concerning such things as the point turbulence intensities, vortex decay rates, turbulence length scales,

correlation factors from statistics software become the means of deducing the length scale. The equation used for the macro length scale is:

$$\Omega = \bar{u} \int_0^{\infty} R(t) dt$$

where the integral is just the area under the correlation curve as the correlation factor R goes from 1 to 0.

Microscopic length scales can be described as those smaller eddies "peeling off" of the major eddy due to shear boundary layer effects between the eddy flow and freestream flow. These micro length scales are the means by which the macro length scale loses energy to the surrounding flow. They can be visualized as minor vortices within a major vortex. The micro length scale is a less descriptive parameter than the macro scale in the scope of this study, but is useful because of its dependence on and description of turbulence eddy and surrounding flow energy difference, not solely a function of the turbulence generation method itself. The equation for microscopic length scale is

$$\lambda = \sqrt{\frac{[-2\bar{u}^2]}{[\partial^2 R / \partial t^2]_{t=0}}}$$

where the denominator can be represented as

$$[\partial^2 R / \partial t^2]_{t=0} = \frac{R_{t=1} + R_{t=-1} - 2R_{t=0}}{\Delta t^2}$$

In words, the micro scale can be mathematically represented according to the slope of the correlation curve at time=0 (Essentially, the initial correlation or macro length scale decay rate).

Other data reduction calculations performed by spreadsheet from HP raw data include Pitot tube velocity from total and static pressures from the incompressible Bernoulli equation,

$$V = \sqrt{\frac{2T_s R \Delta P}{P_{atm}}}$$

and constant resistance hot wire velocity from voltage difference

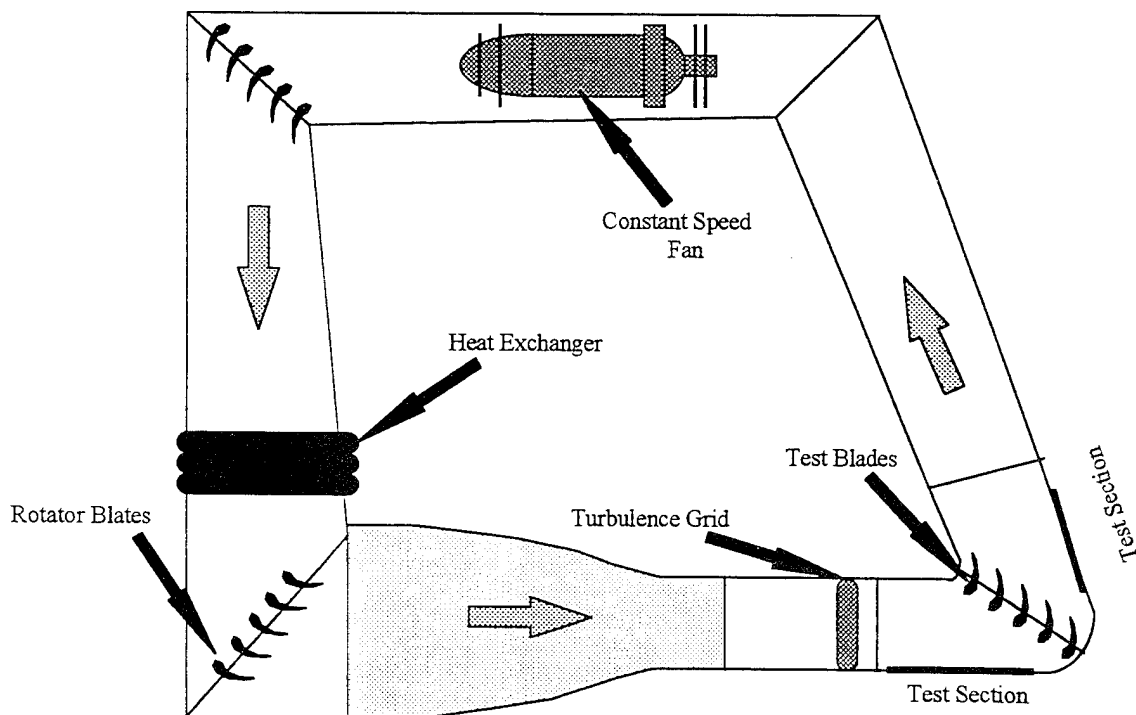
$$V = C_0 + C_1(e_o - e) + C_2(e_o - e)^2 + C_3(e_o - e)^3 + C_4(e_o - e)^4.$$

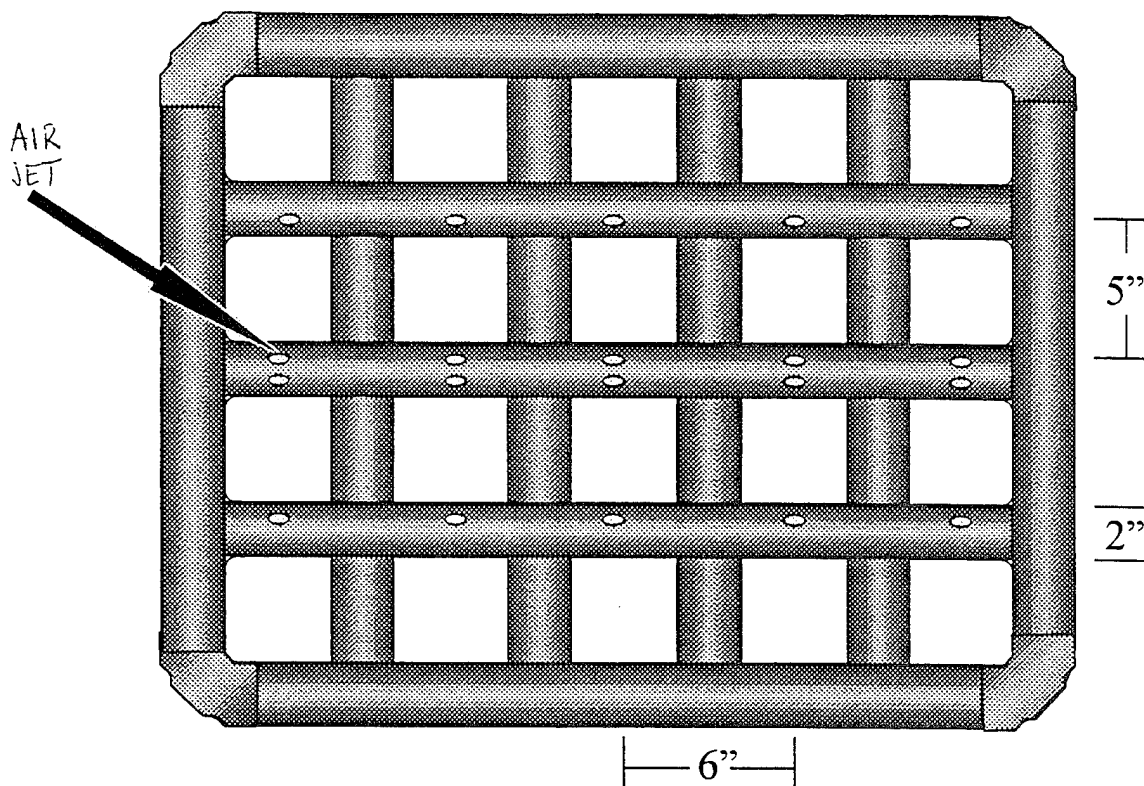


### Setup:

The theory behind a Cascade Wind Tunnel is that it simulates flow over an array of turbine blades. This is accomplished by turning the flow through an angle of  $105^\circ$  as it passes through the test section (see Figure 2 below). Therefore, the supposed result is that each blade sees the same flow qualities, changing direction with the camber of the blade, void of interference from neighboring blades. Turbulence can be produced by a grid (see Figure 5 below) perpendicular to the flow which can supplementally inject pressurized air across the steady streamline flow. These air jets produce a significant increase in the turbulence levels from those obtained with the grid obstruction alone- more characteristic of post-combustion levels. The turbulent flow then enters the array of blades at a  $43.3$  degree angle, the distance downstream from the grid being the main determinant of turbulence intensity. The flow then leaves the blade aligned in a trailing edge alignment due to the "bent" test section (more accurate from a modeling perspective in simulating arrays of repeating blades). The behavior of turbulence and heat transfer in such a model is significantly different from that obtained in "straight" wind tunnels.

The following diagrams show various key aspects of the experimental setup.





**Figure 5. Turbulence Generation Grid**

Setup values consistent for each traverse run were a 7500 Hz sampling rate (used both as individual data and for time averaged values), grid air pressure of 57 psi, traverse steps of 2", and traverse placement of 22.5" from the leading edge line of the array. The array itself consisted of five 6.5" spaced scaled-up Langston turbine blades.

#### **Calibration:**

The majority of equipment used was already calibrated prior to the beginning of the flow quality study, and was seen to be so by preliminary verification runs of the facility. A digital pressure transducer calibrated by the USAFA PMEL facility was used as the secondary standard in a manometry based pitot-static system. Based on the output of this system, the general fourth-order equation (mentioned above) for dynamic hot-wire voltage measurements was supplied with the appropriate constants (listed in Appendix J). However, due to a since changed bias in the system as evidenced in early pitot-hot wire comparisons, the hot wire was thereafter statically calibrated following each run by manually adjusting the velocity conversion  $e_0$  (the "no flow"

length scales according to eddy flow energy. Also use the 7500-sample mean and standard deviation to validate spreadsheet turbulence intensities at centerline.

i. Repeat steps f. and g. for different grid positions and repeat runs for air on/off and grid x position.

j. Perform this procedure at exponentially changing distance increments (constant  $T_u$  increments) over the maximum streamwise range of the grid.

k. Analyze the data, first discussing turbulence production validity (magnitude) and second discussing turbulence conditions with respect to the blade array (uniformity and trends).

### Results:

The experimental results are mainly in graphical form located in Appendices. The graphical trends and significant numerical results will be discussed in this section.

The grid placement analysis in Appendix A proved to be accurate for predicting the trend of turbulence intensity vs. distance (a  $-0.71$  power curve according to Roach) for the air off grid. Appendices G and H contain equation-labeled curves of the experimental results. This is reinforced in Appendix F where grid air on and air off are plotted across the center horizontal span of the tunnel, which due to the traverse (blade cascade) angle incorporates a change in x-distance. However, with air jets on, the decay rate is decreased slightly, with turbulence intensity equalling a function of approximately  $x^{-5}$ , due to the more energized nature of the flow. Magnitude is not of concern here. The slope of the turbulence intensity versus grid distance, or the decay rate, is. Variations that do occur in magnitude, that is, in the value of the constant multiplier, can be accepted since it is relatively simple to obtain a single location grid-specific test for C, and make predictions from there on. The range achieved in analysis of the "area of interest" with air jets off was from about 7-11%, as predicted in Appendix A. Air jets on is a unique case for the facility and could not be accurately predicted prior experimentation.

Appendix B, tunnel temperature verses time, shows the facility to have been controlling the temperature in a periodic fashion to obtain the desired mean of  $19^{\circ}\text{C}$ . Though the thermocouple was located in the turbulent portion of the flow, on the traverse arm, no correlation can be seen between temperature and position, or temperature and turbulence intensity (note that "Traverse Measurement #," as shown, can not be directly visualized as horizontal or

here to horizontal distance due to traverse geometry) across the central 12 inches of the tunnel the air on condition, due to an unexpected air jet coalescence pattern, consistently shows two peaks (turbulence) or valleys (velocity) in the central region of interest. Since this will cause the test blade to be subjected to incidents different flow conditions depending on surface position, this result is grounds for redesigning the air-supplemented turbulence grid, most likely with relocation of the air jets, smaller rod diameter, or both. In general, though, the turbulence decay rate, that is, the slope of Roach's correlation, is small enough so that the detrimental effect of combining a perpendicular grid with an angled cascade is negligible with a single, central test blade.

Finally, the macroscopic and microscopic length scale descriptors of turbulent flow were found to increase slightly with distance downstream, but this increase can be considered insignificant along the 35 inch distance covered in this experiment. Graphs showing this can be referenced in Appendix I. Macroscopic length scales of 1.5" with air jets off and 1.75" with air jets on, and microscopic length scales of about 0.3" for both conditions were produced. Another result of the length scale study was that macroscopic length scales, although labeled with a mean here, are very difficult to predict, having variations as great as  $\pm 1$ " off the expected smooth line trend. The correlation factor for the data points in Appendix I is much too small to make accurate predictions of macro length scales.

#### **Uncertainty/Error Analysis:**

As discussed in the Theory section the following is the equation used to calculate turbulence intensity from voltage and velocity measurements:

$$Tu = \frac{dV}{d(\Delta e)_{vm}} \left( \frac{e}{V} \right) 100\%$$

When applied in a spreadsheet for coordinate quality mapping of the flow field, an estimation method is used in above equation to obtain turbulence intensities at each point in the flow. Average velocity and standard deviation are calculated numerically, approximating the fourth order velocity-voltage curve with linear segments between voltage increments (over 7500 Hz hot-wire sampling frequency). The fourth order curve can, however, be more accurately analyzed for velocity and standard deviation (thus turbulence intensity) using a curve fit equation (discussed below) in computer software. Thus a more accurate method is to take all 7500 values and reduce them with an iterative statistical program. This becomes highly impractical due to

variation in flow quality across the central test section region.

This study should pave the way for future work with improved turbulence generation methods, and as a prediction tool for studying the effects of turbulence on turbine blade heat transfer, the purpose of an Aero-thermal Cascade facility.

## **APPENDIX A**

### Grid Placement Analysis

## **APPENDIX B**

### Tunnel Temperature Fluctuation Graphs

Chart1

Tunnel Temperature with Air Jets OFF

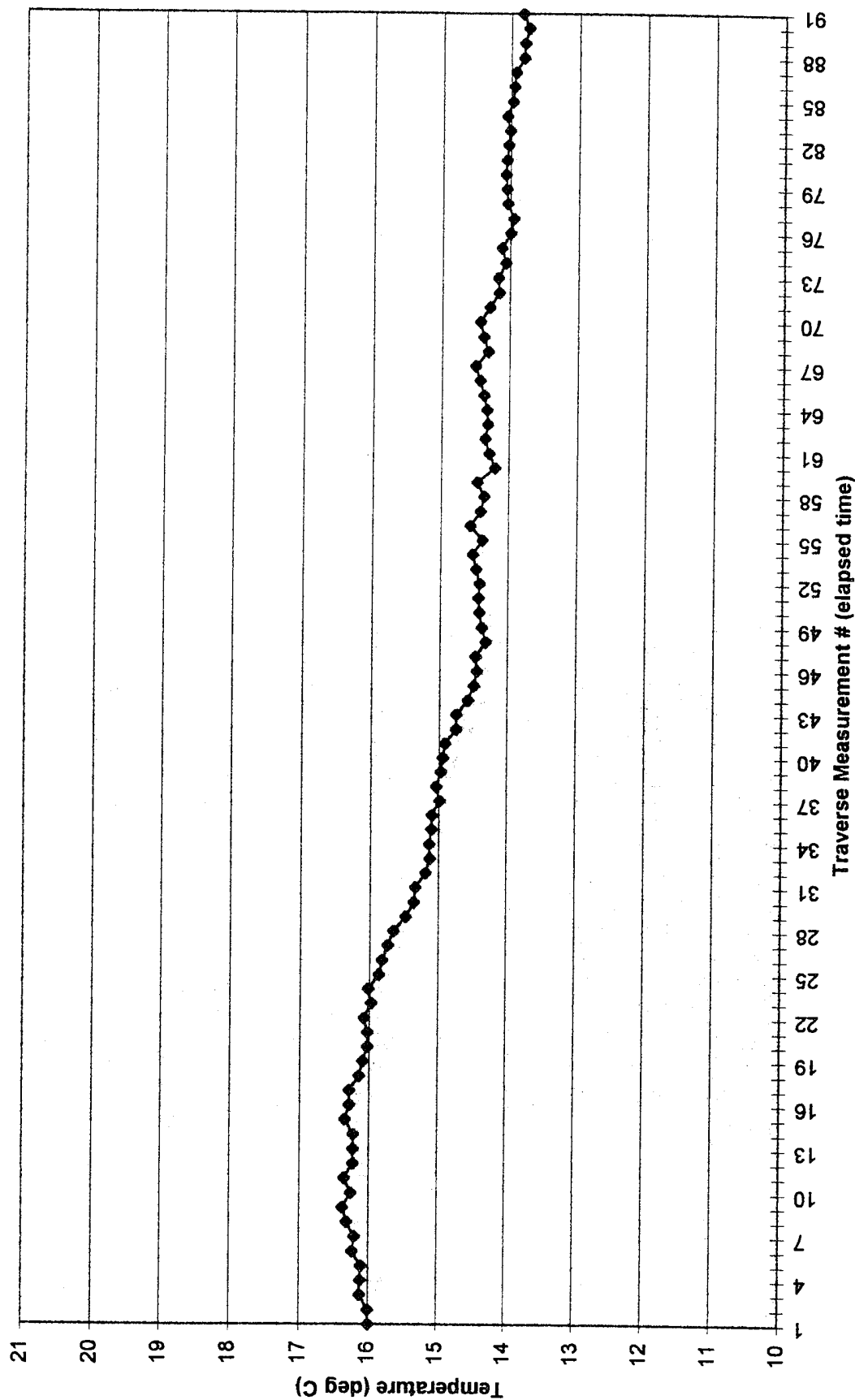




Chart1

# Tunnel Temperature with Air Jets ON

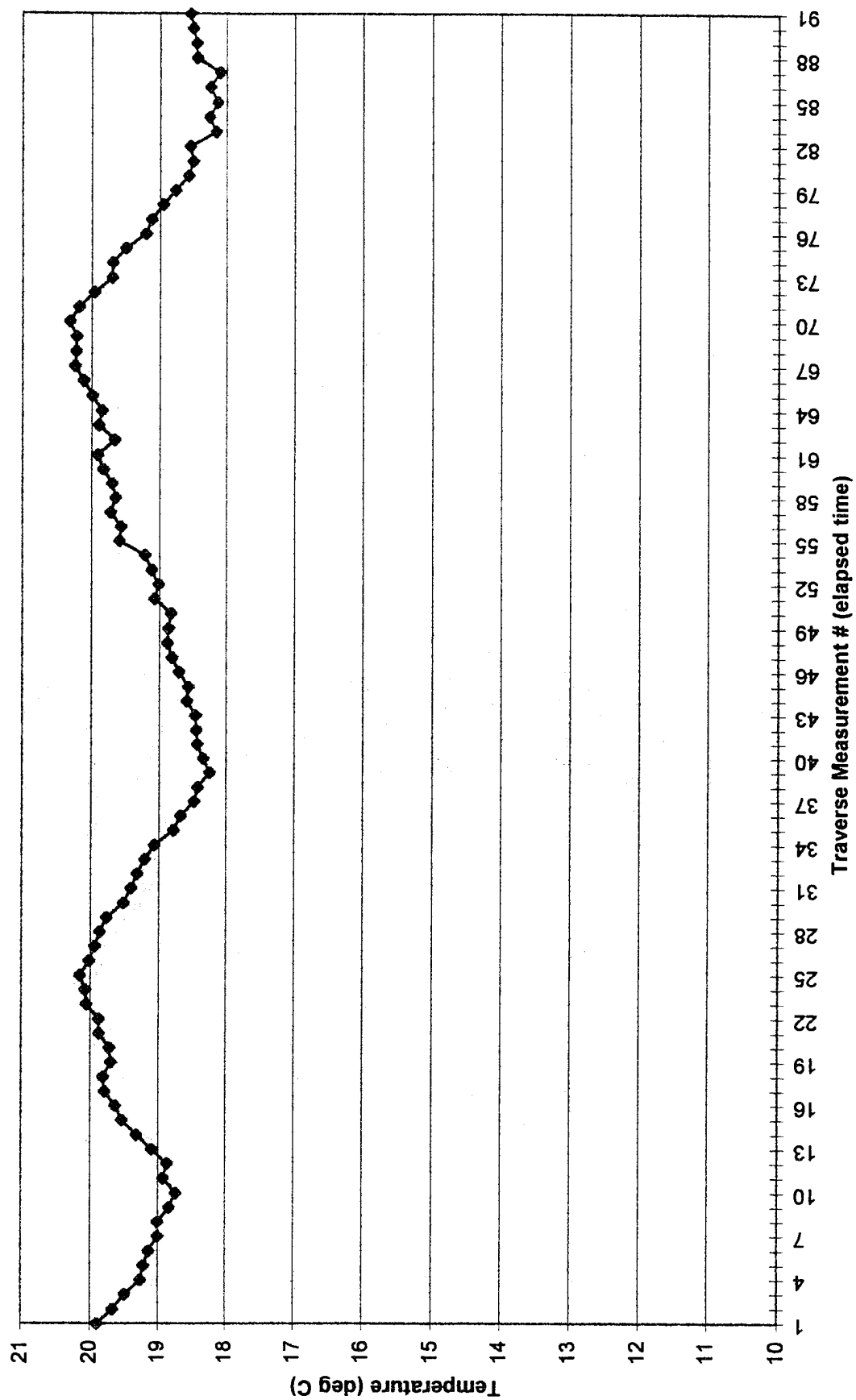


Chart1

Tunnel Temperature with Air Jets OFF

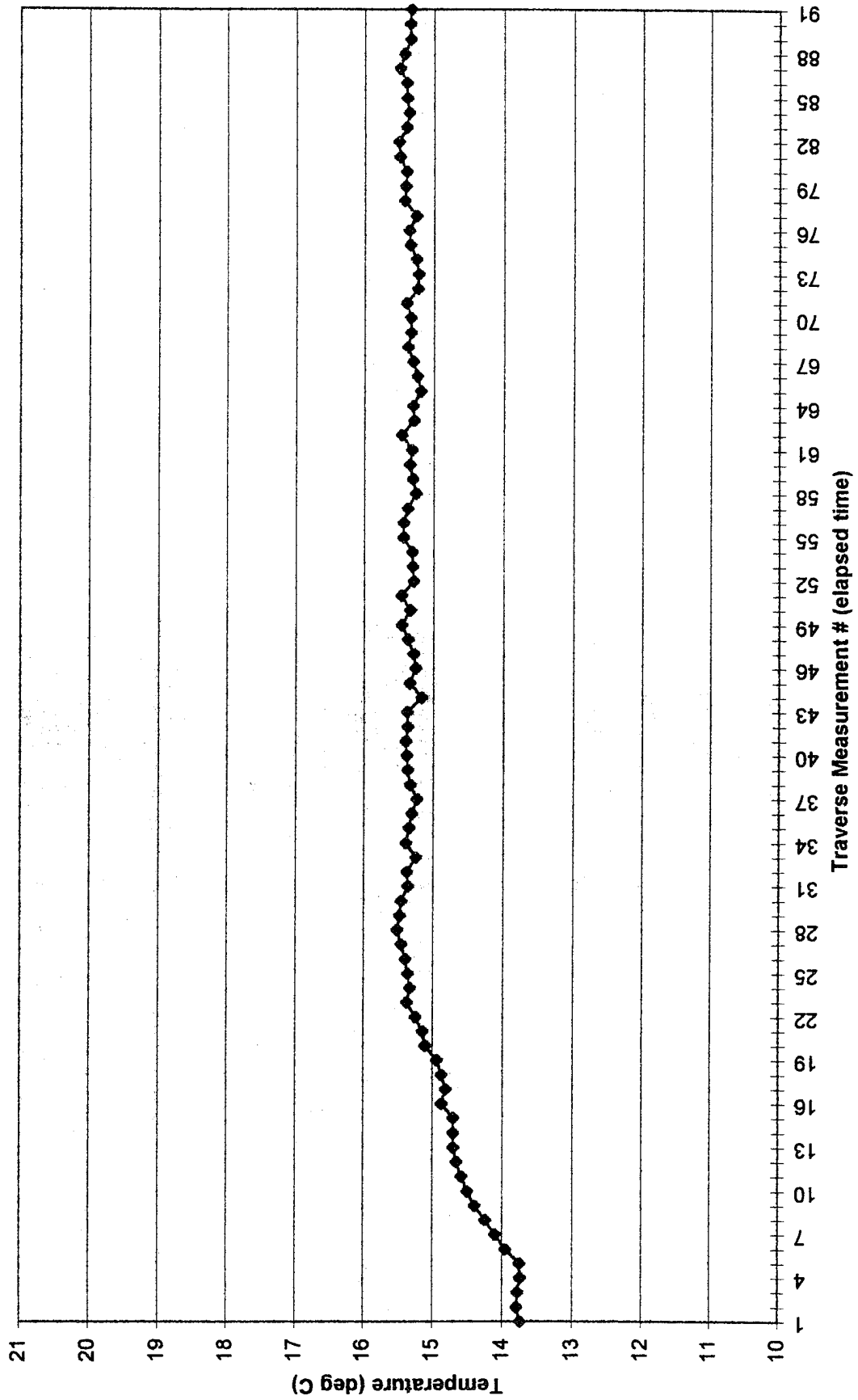


Chart1

Tunnel Temperature with Air Jets ON

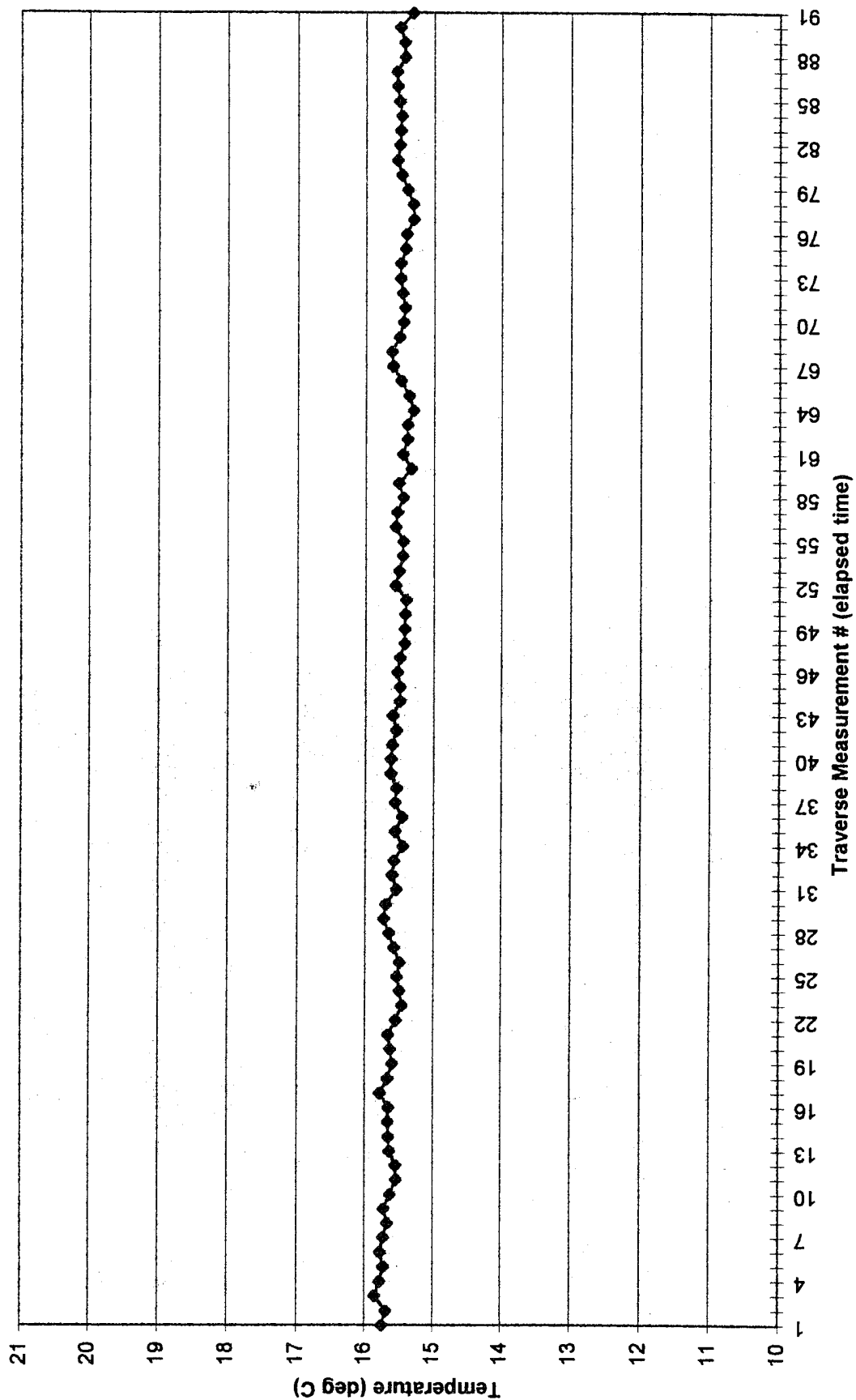


Chart1

Tunnel Temperature with Air Jets OFF

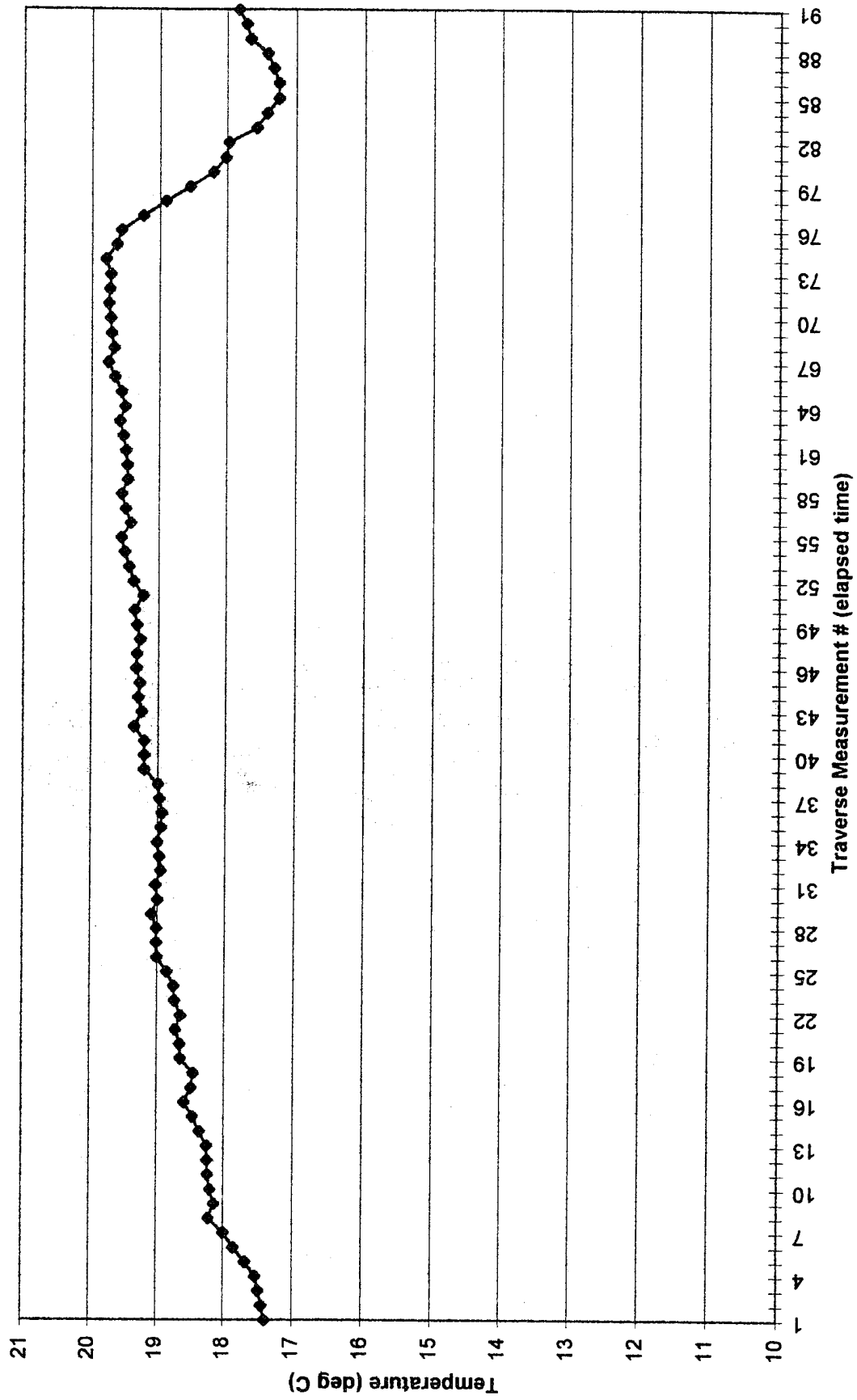


Chart1

Tunnel Temperature with Air Jets ON

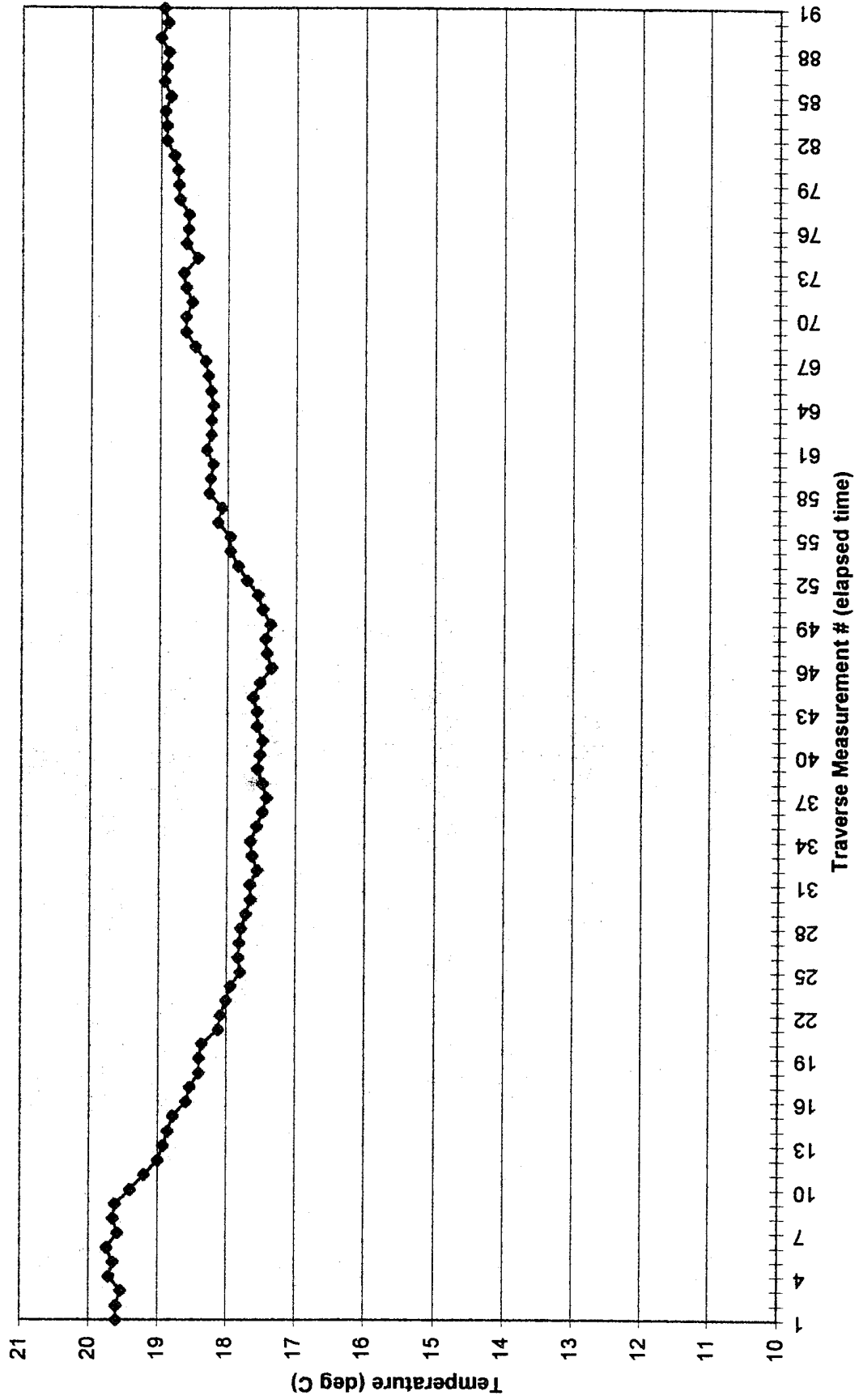


Chart1

# Tunnel Temperature with Air Jets OFF

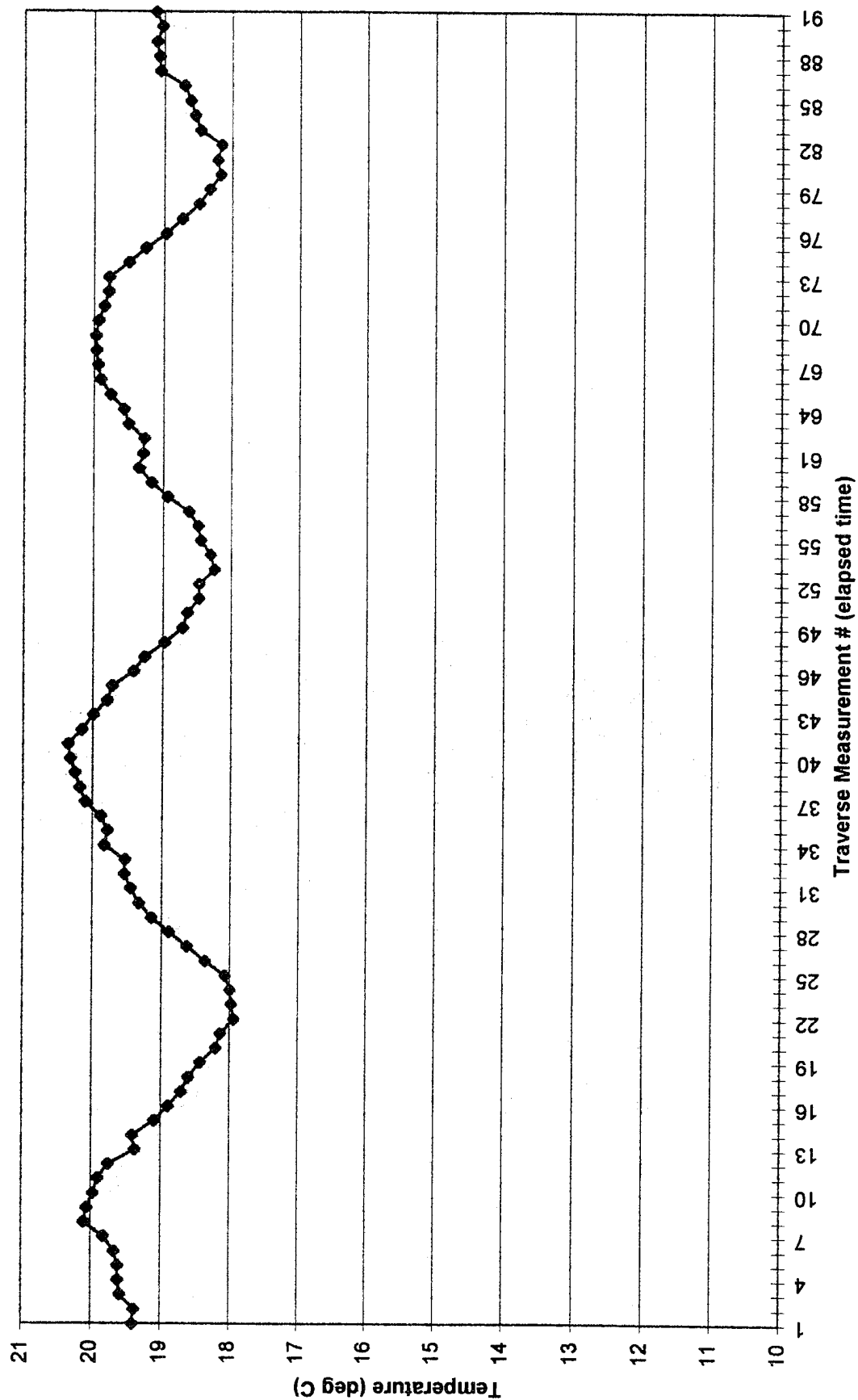


Chart1

Tunnel Temperature with Air Jets OFF

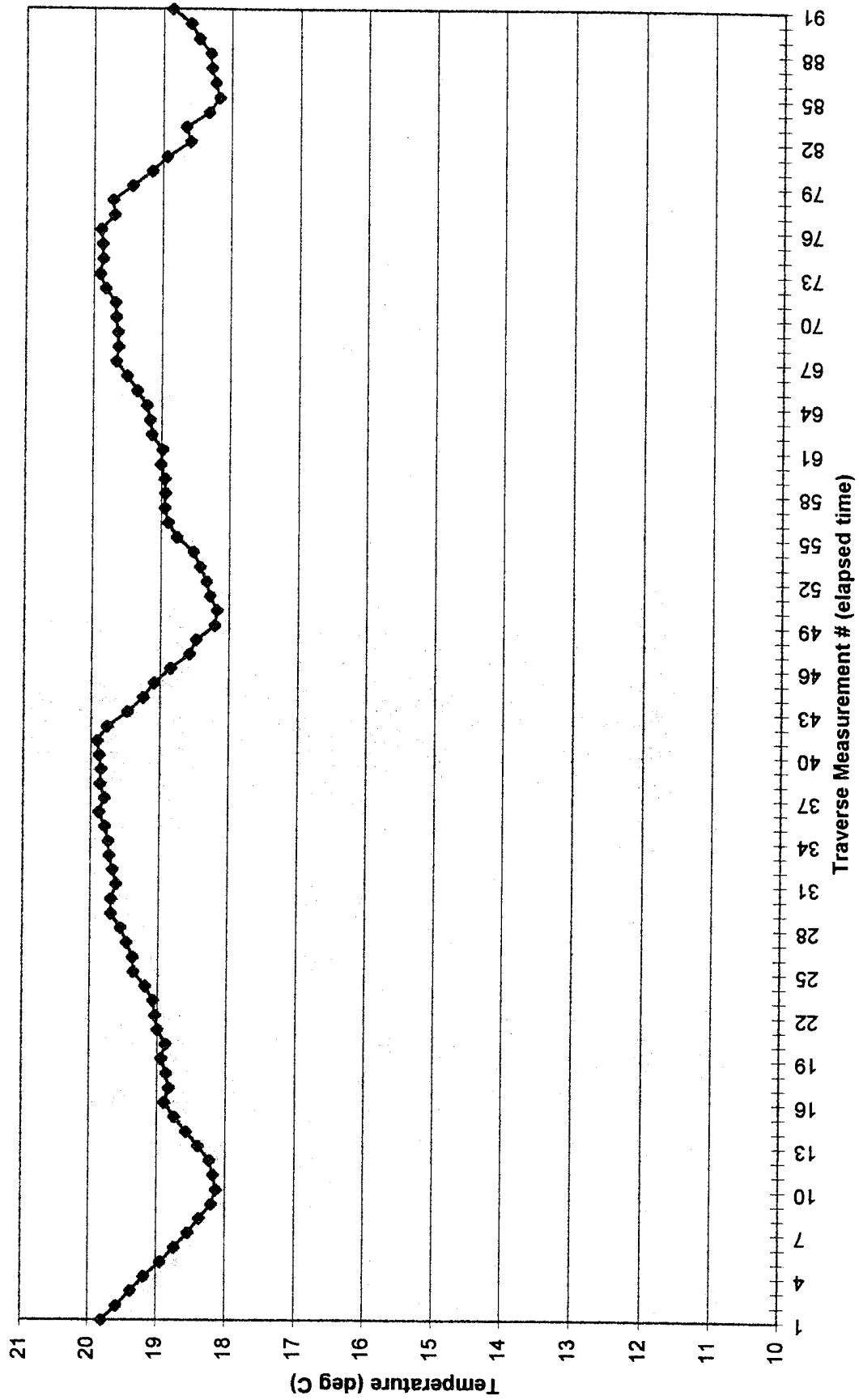


Chart1

# Tunnel Temperature with Air Jets ON

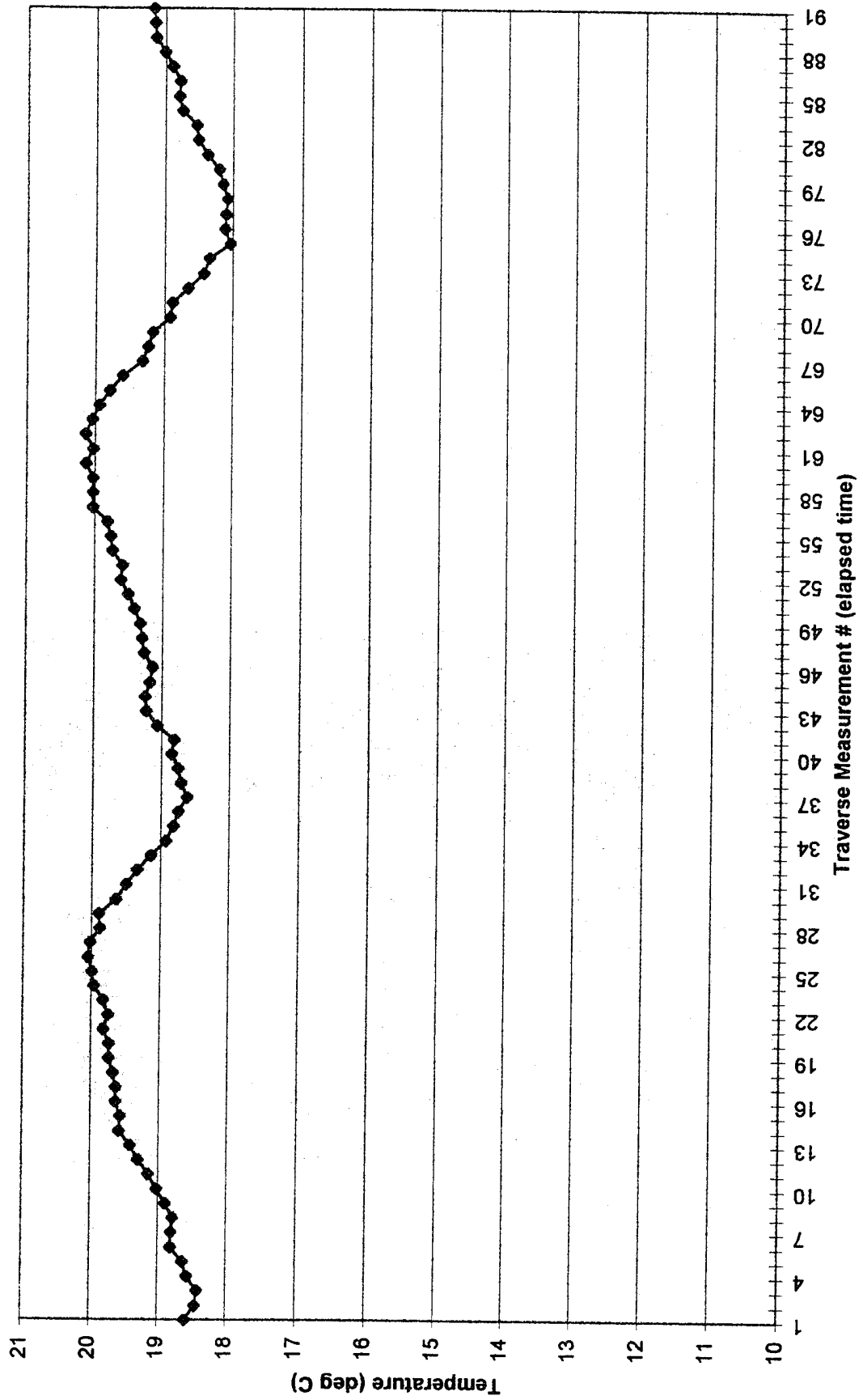




Chart1

### Tunnel Temperature with Air Jets OFF

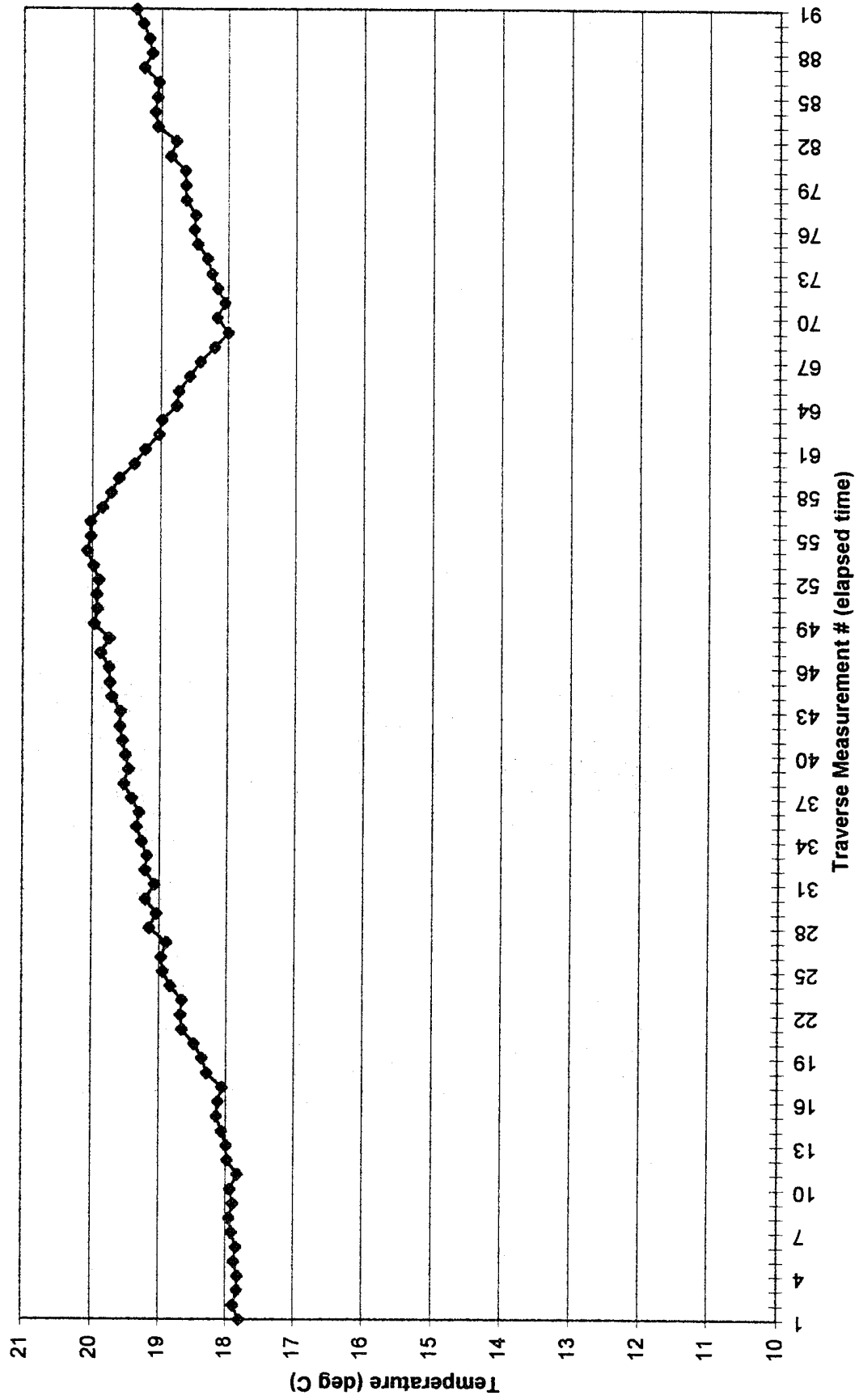
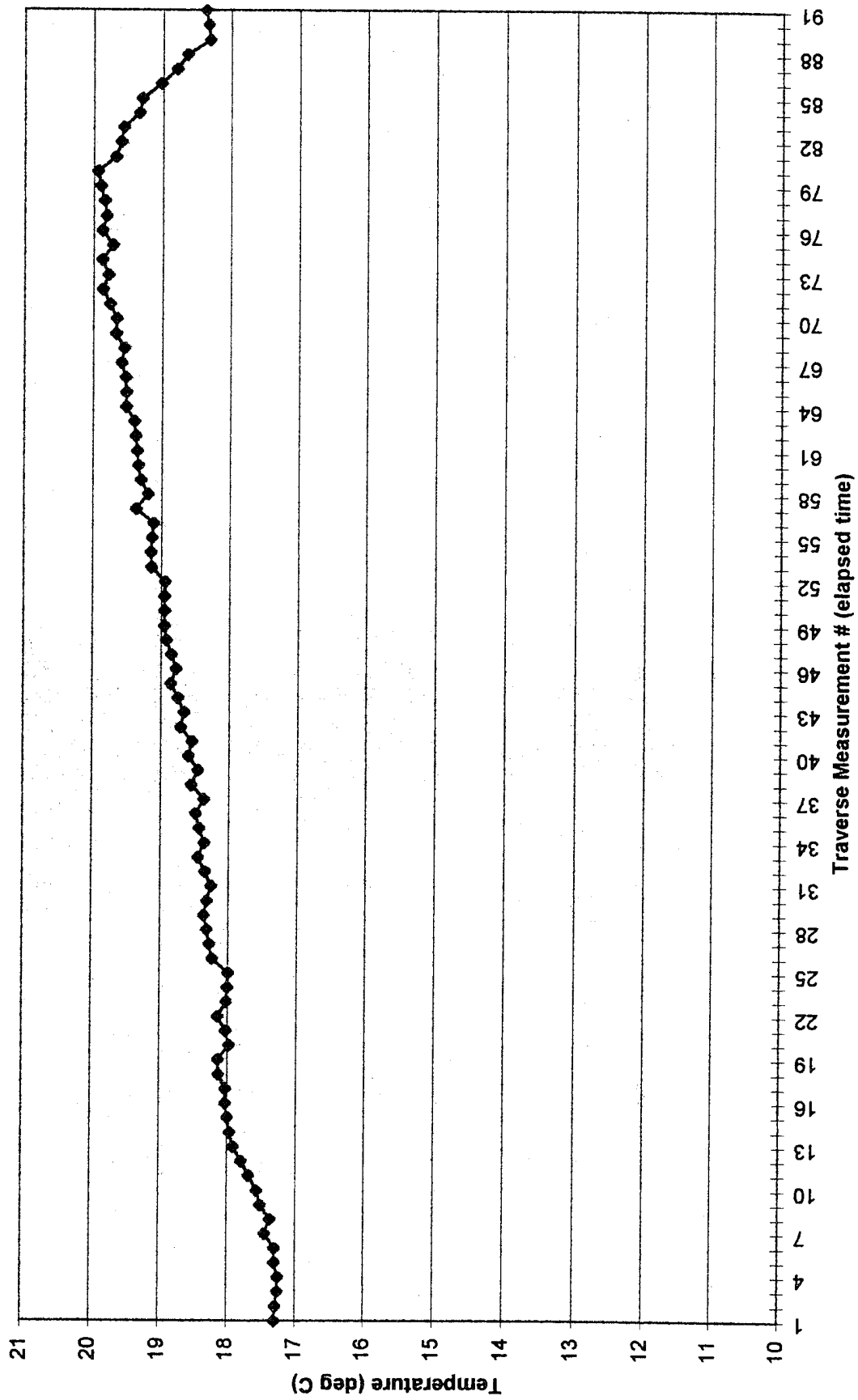


Chart1

Tunnel Temperature with Air Jets ON



## **APPENDIX C**

### Velocity Distribution Plots

Chart2

Velocity Distribution for Air Jets OFF - x=32

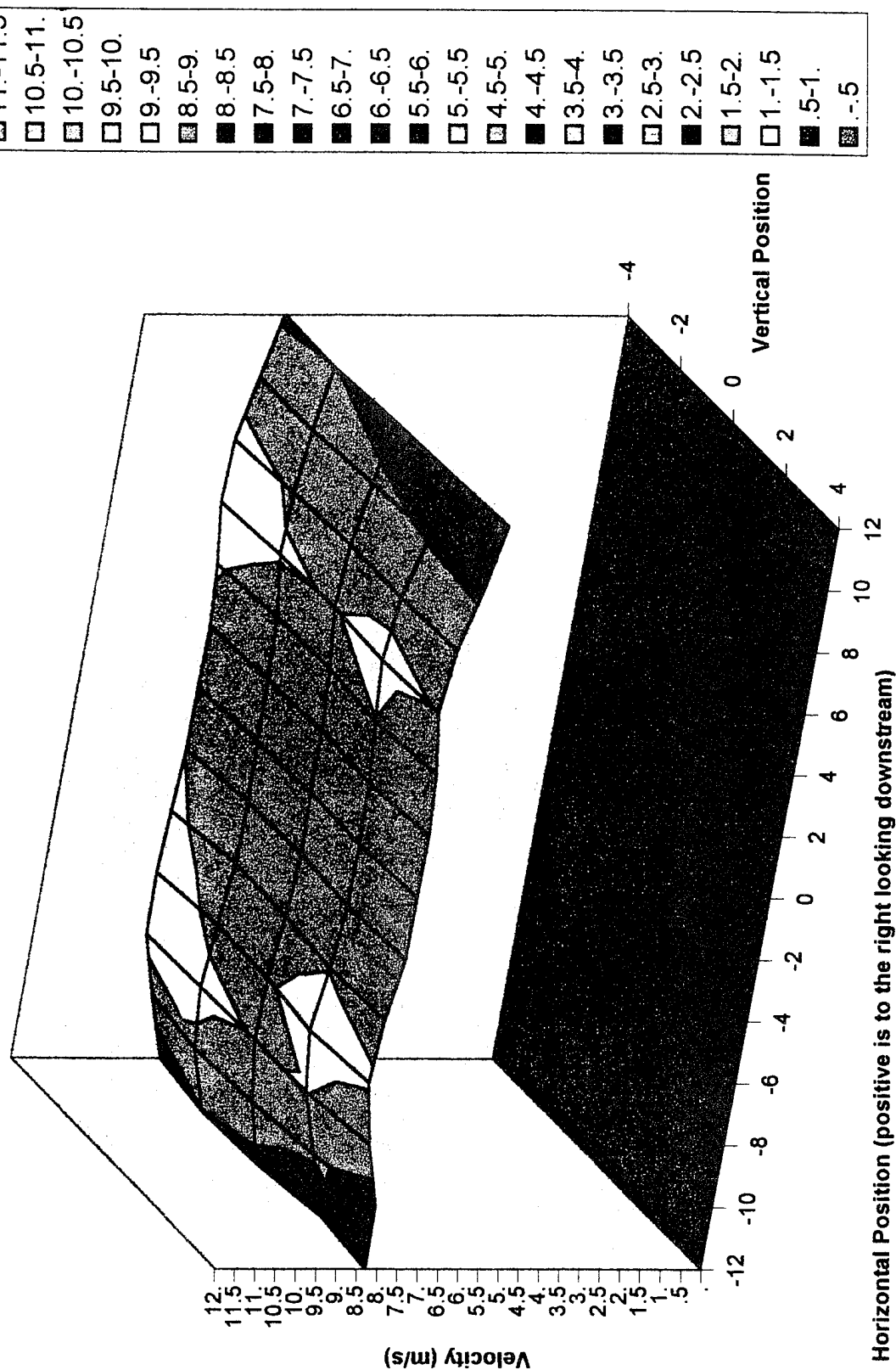
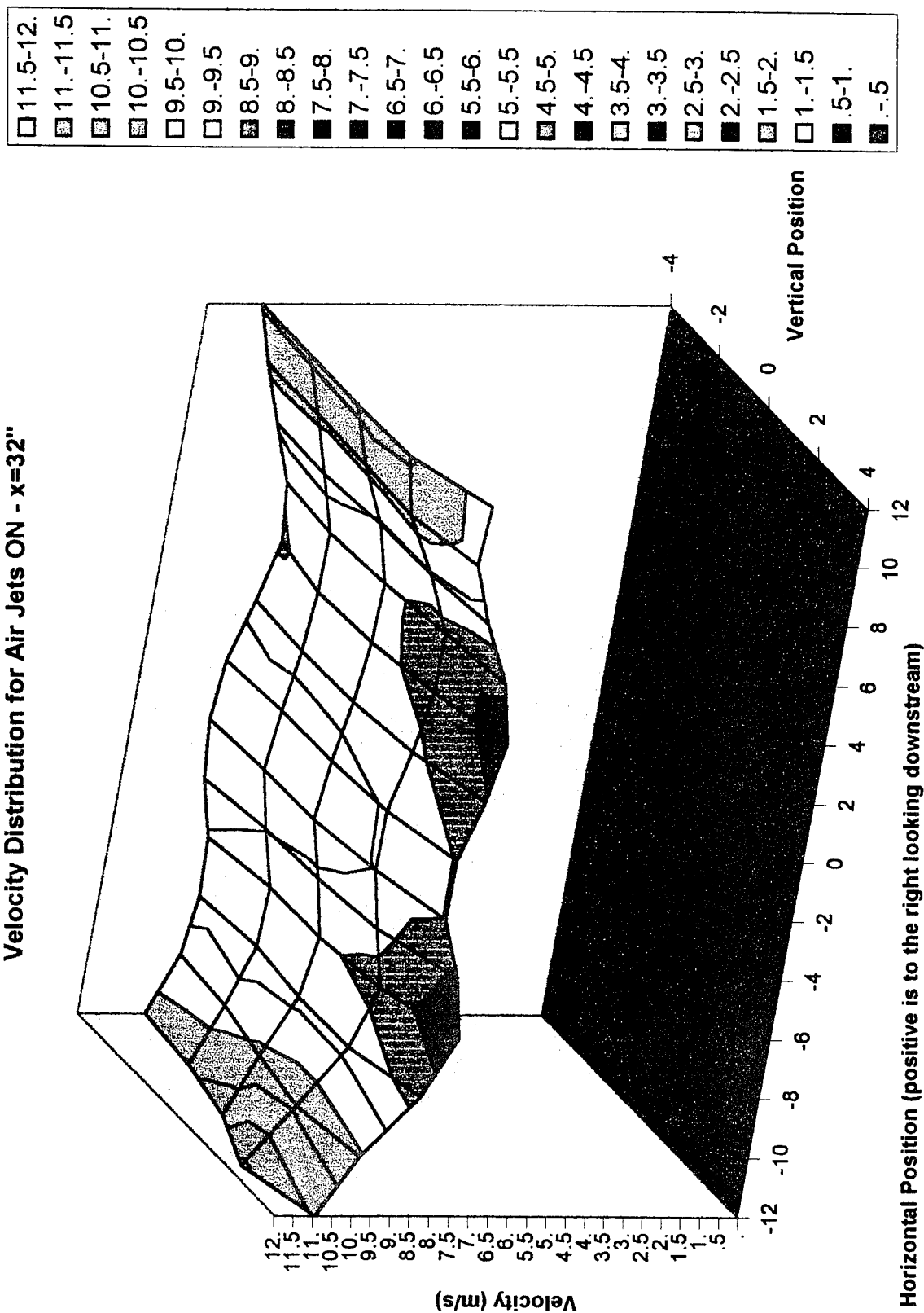


Chart2

Velocity Distribution for Air Jets ON - x=32"



Velocity Distribution for Air Jets OFF - x=35.75"

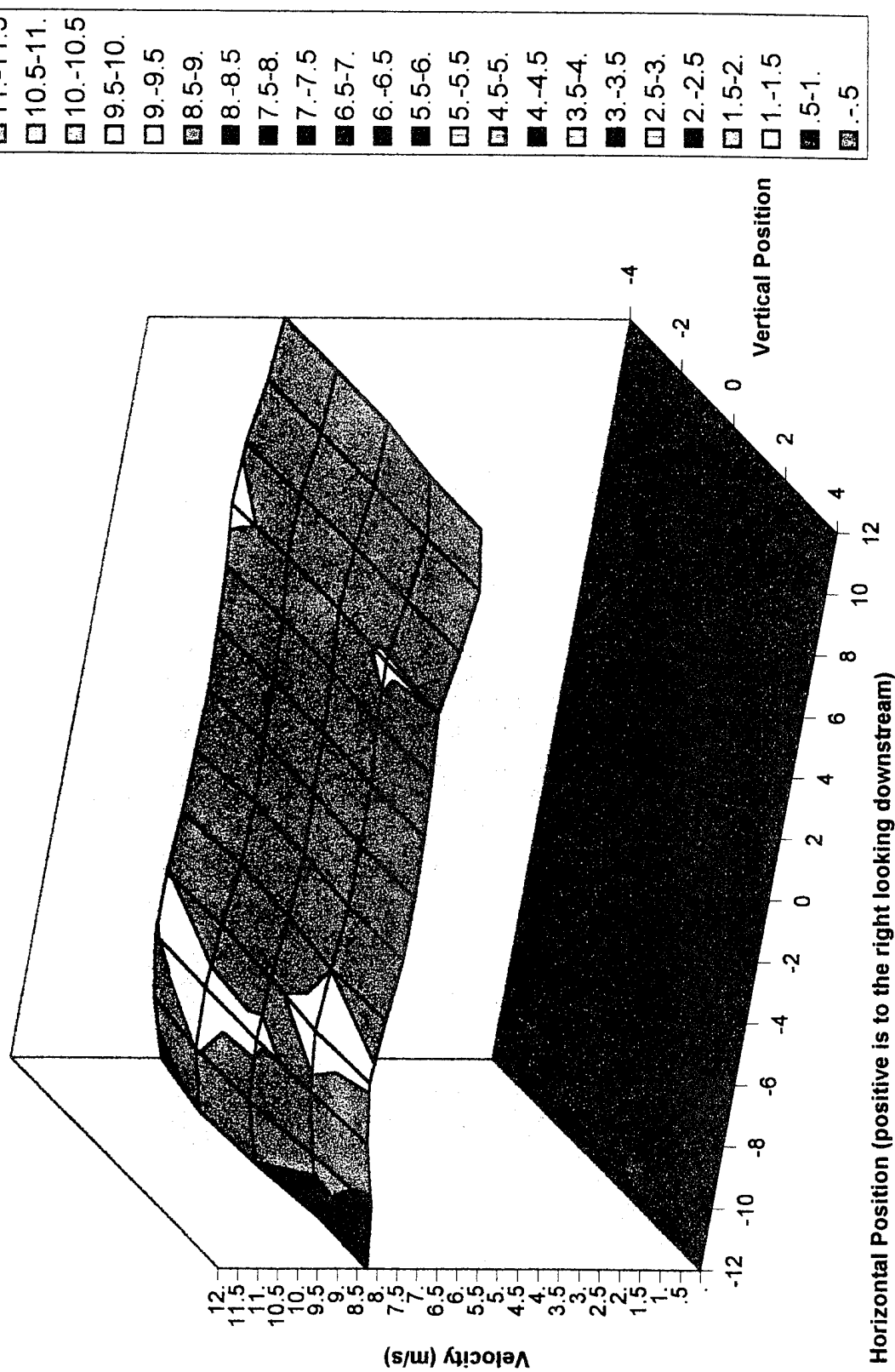


Chart2

Velocity Distribution for Air Jets ON - x=35.75"

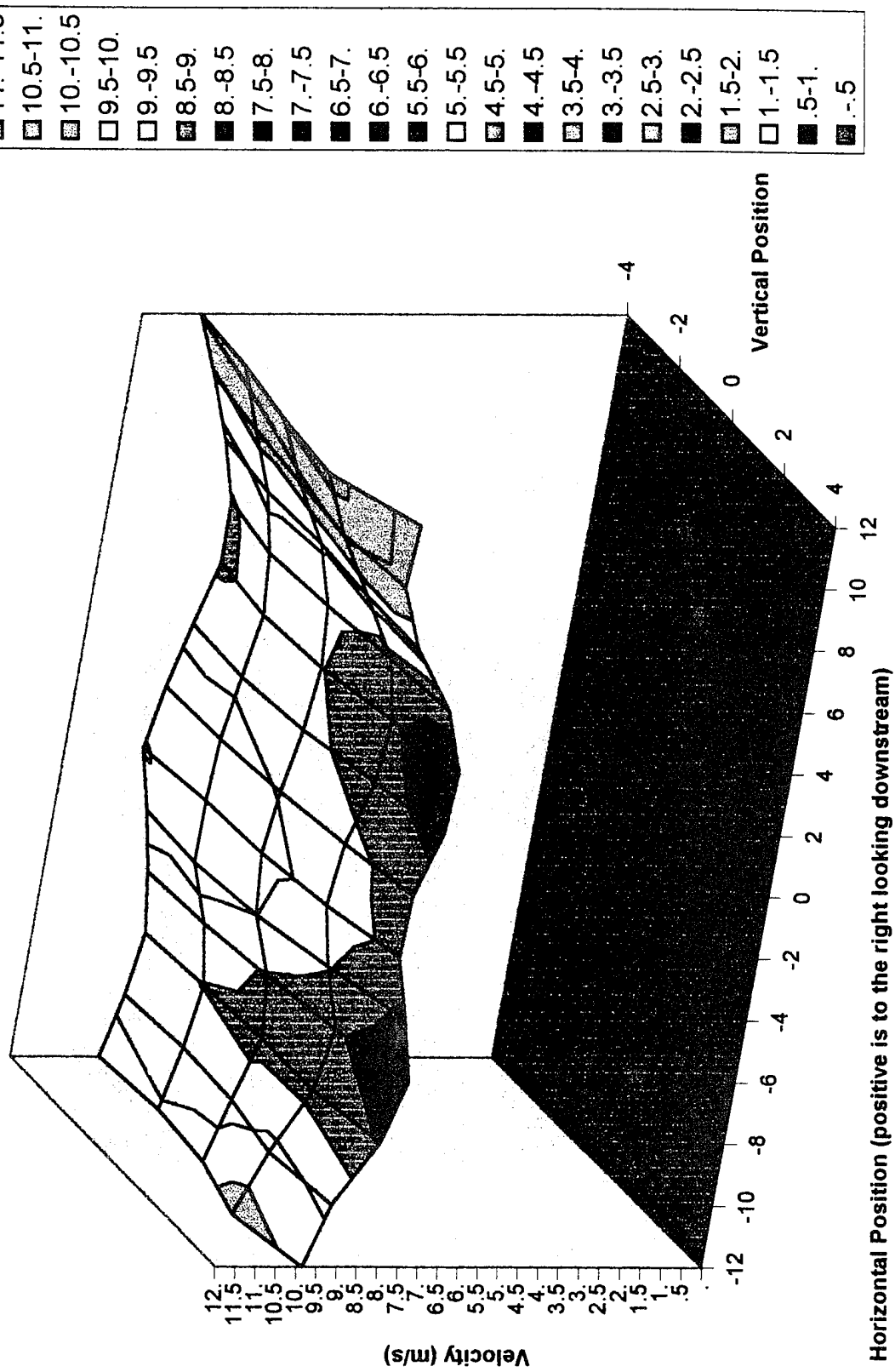
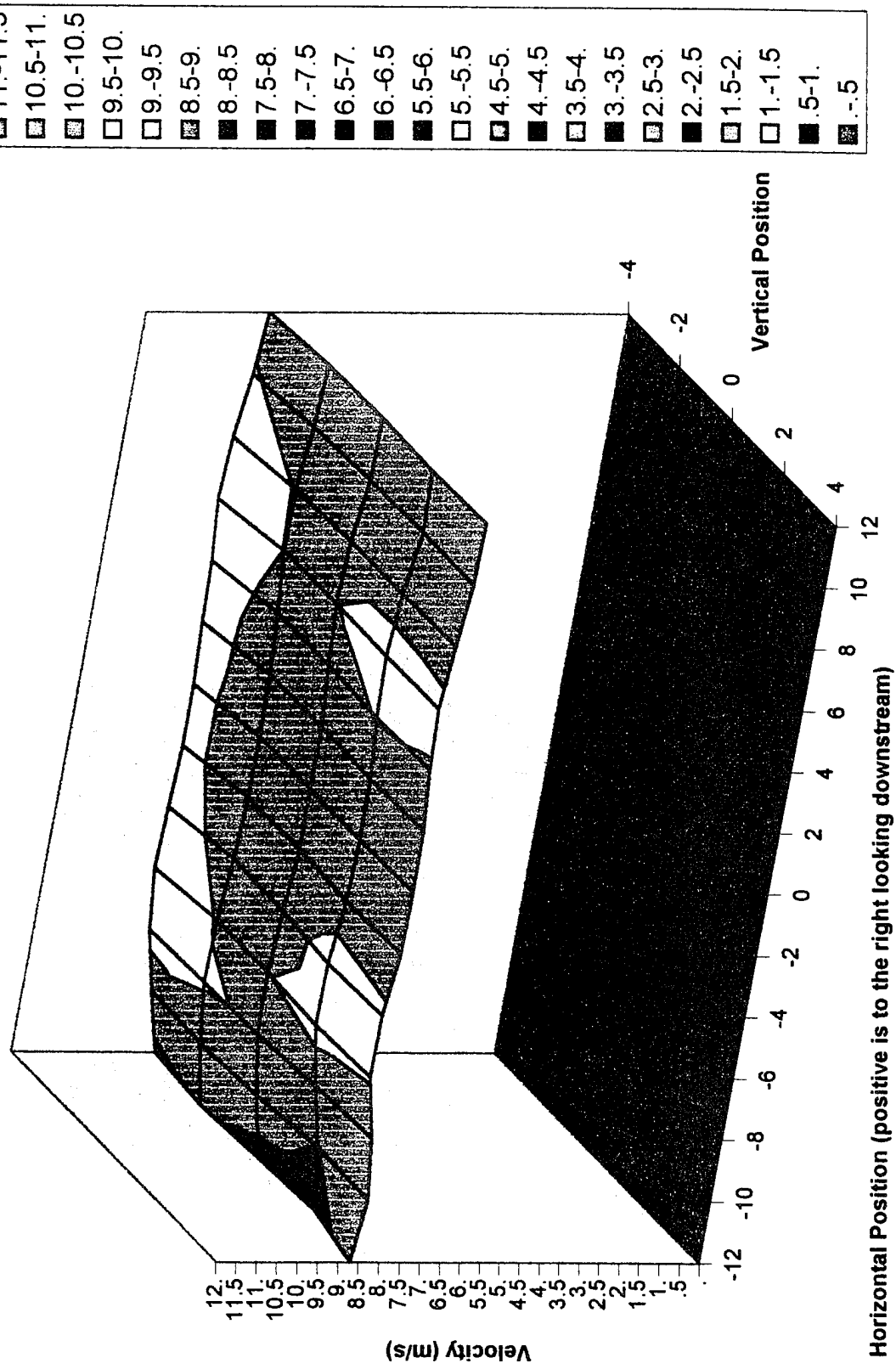


Chart2

Velocity Distribution for Air Jets OFF - x=40"





Velocity Distribution for Air Jets ON - x=40"

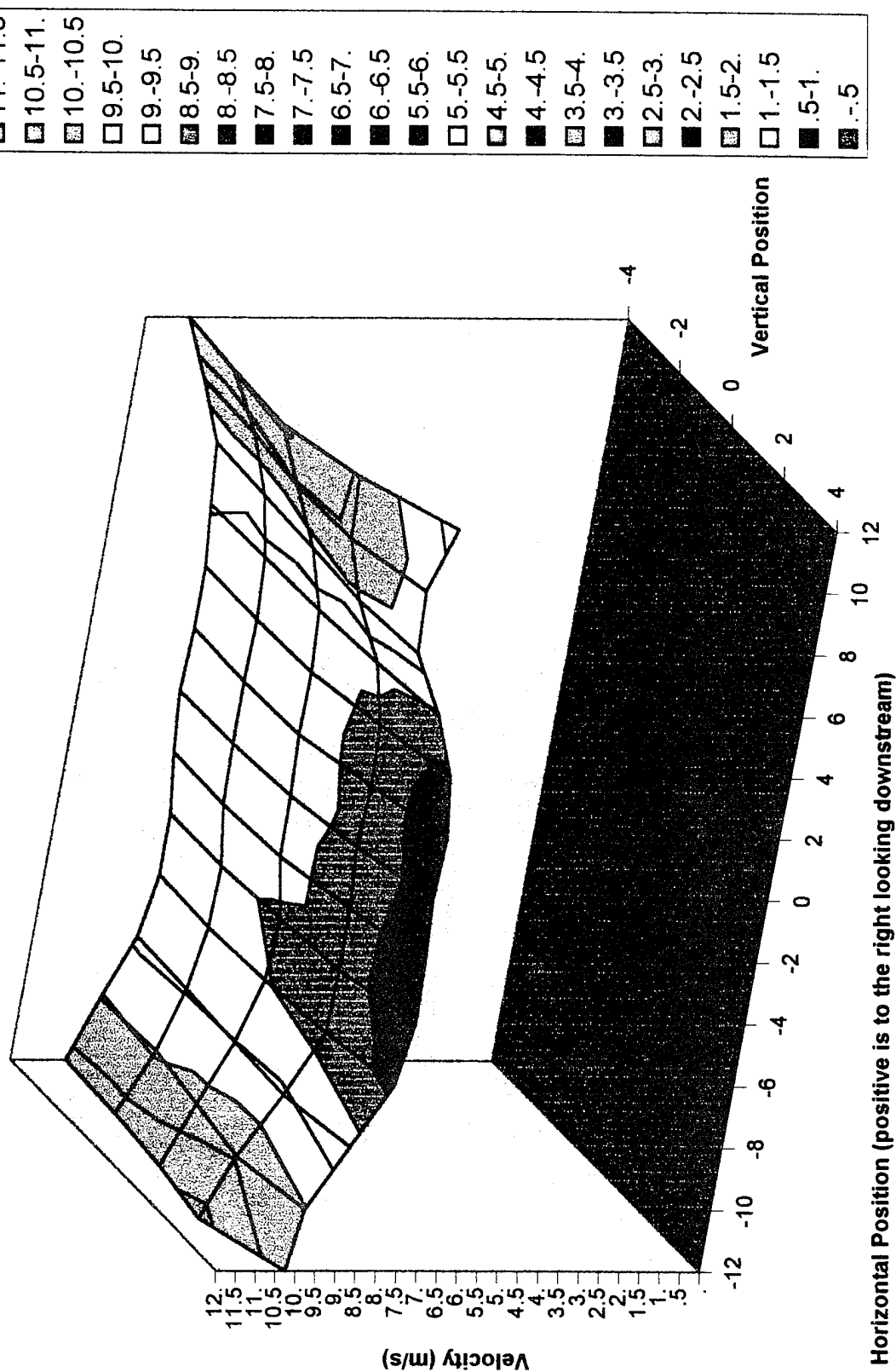
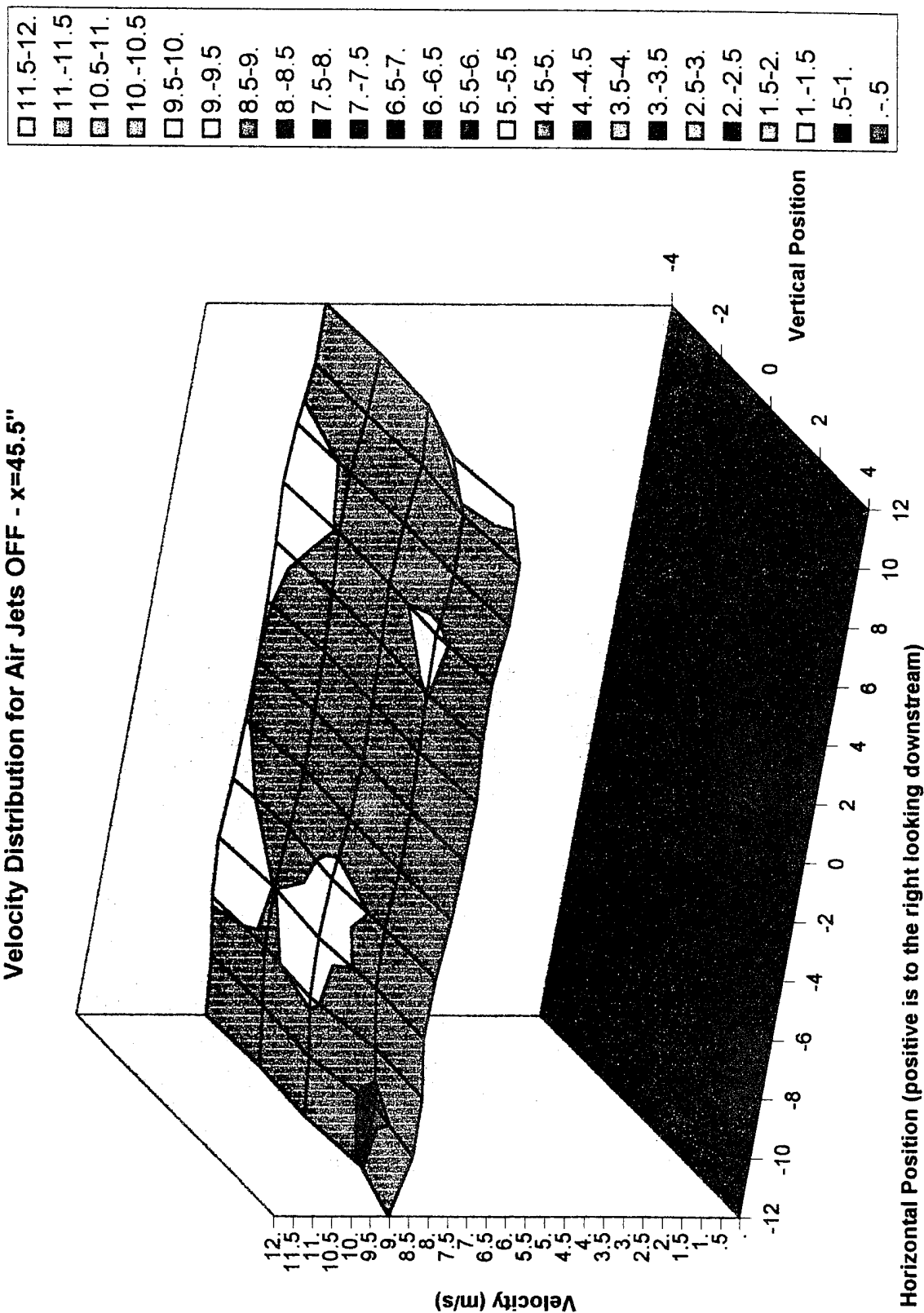


Chart2

Velocity Distribution for Air Jets OFF - x=45.5"



Velocity Distribution for Air Jets OFF - x=52"

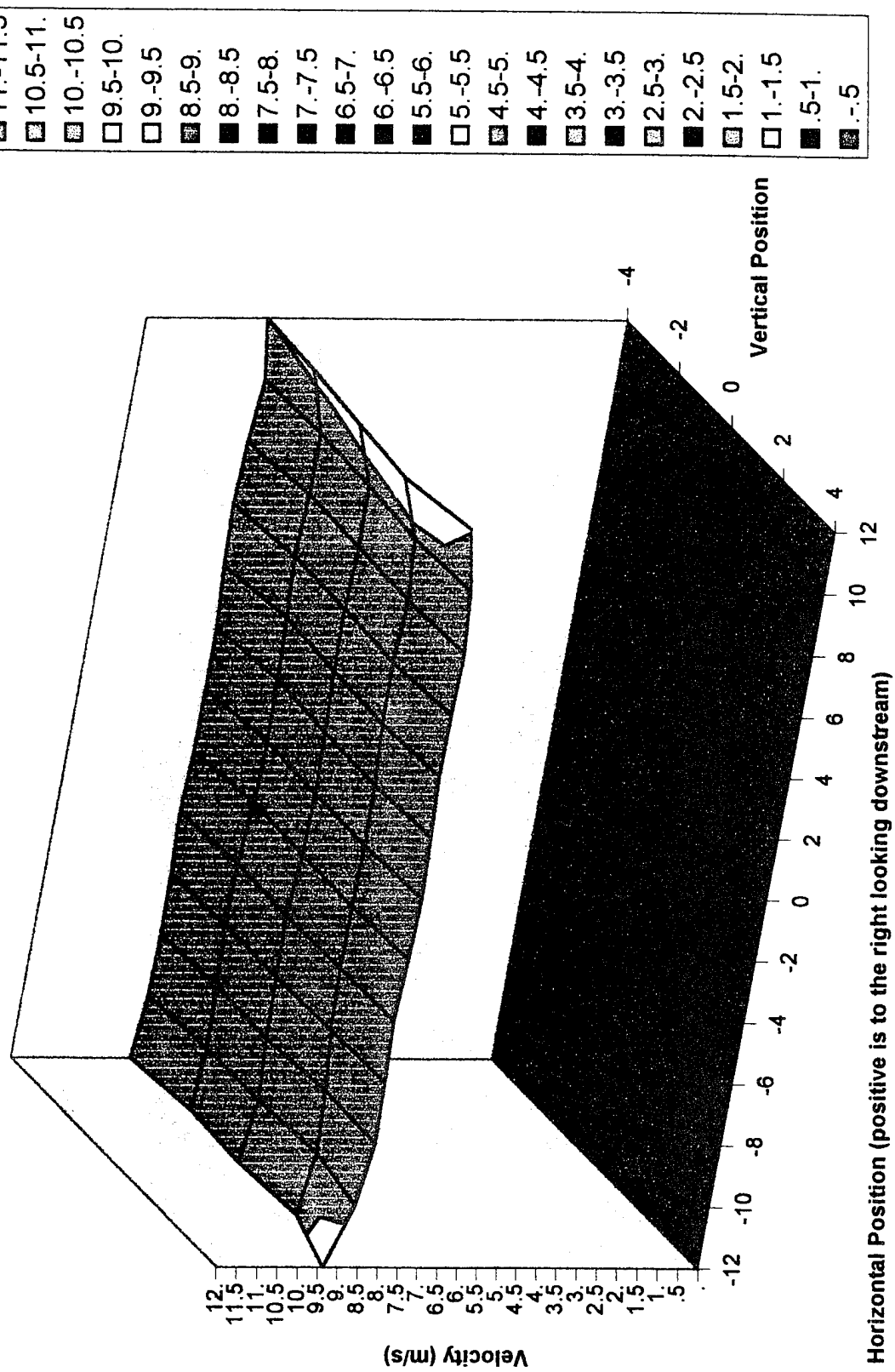


Chart2

# Velocity Distribution for Air Jets ON - x=52"

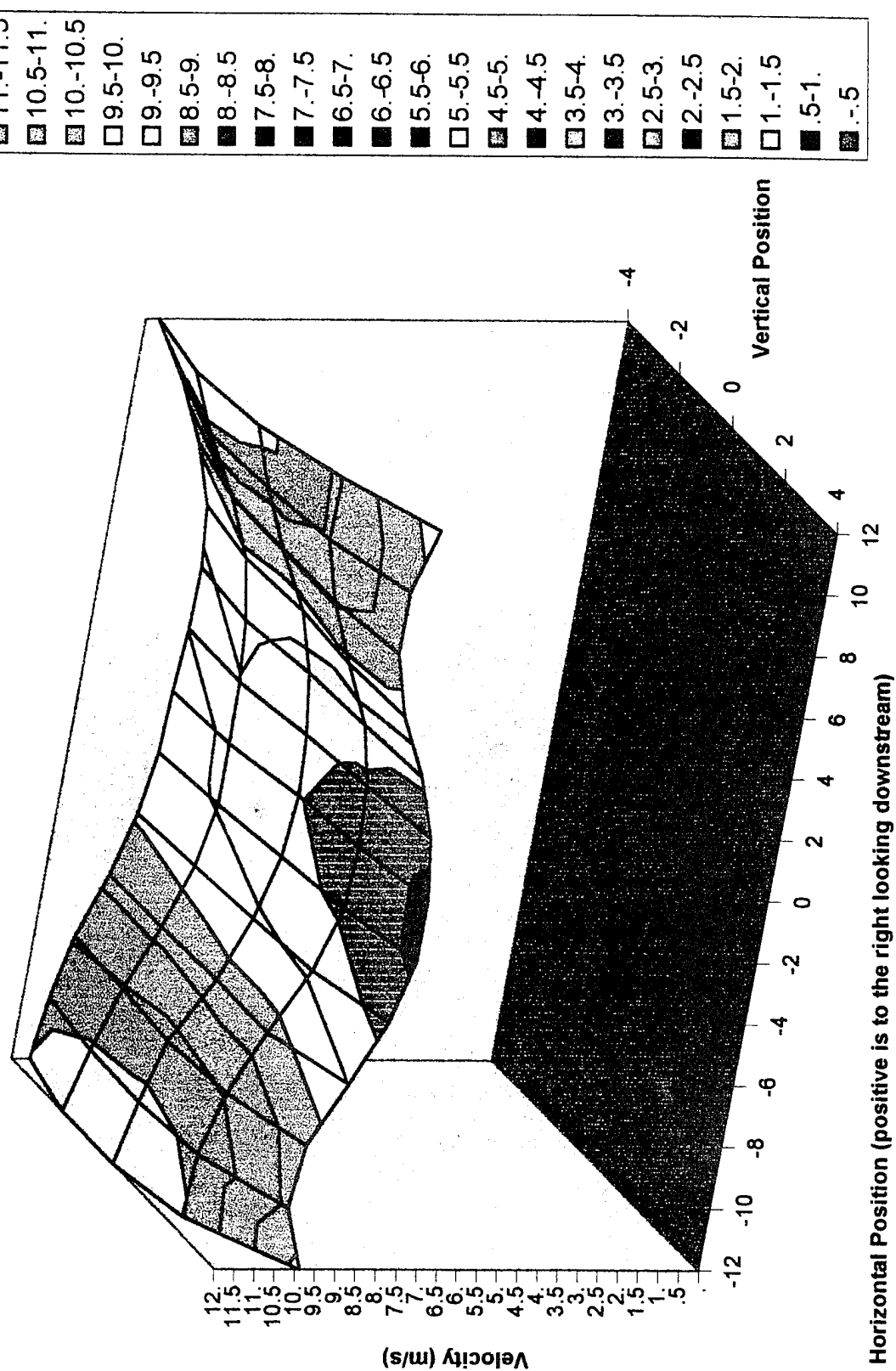


Chart2

Velocity Distribution for Air Jets OFF - x=67.5"

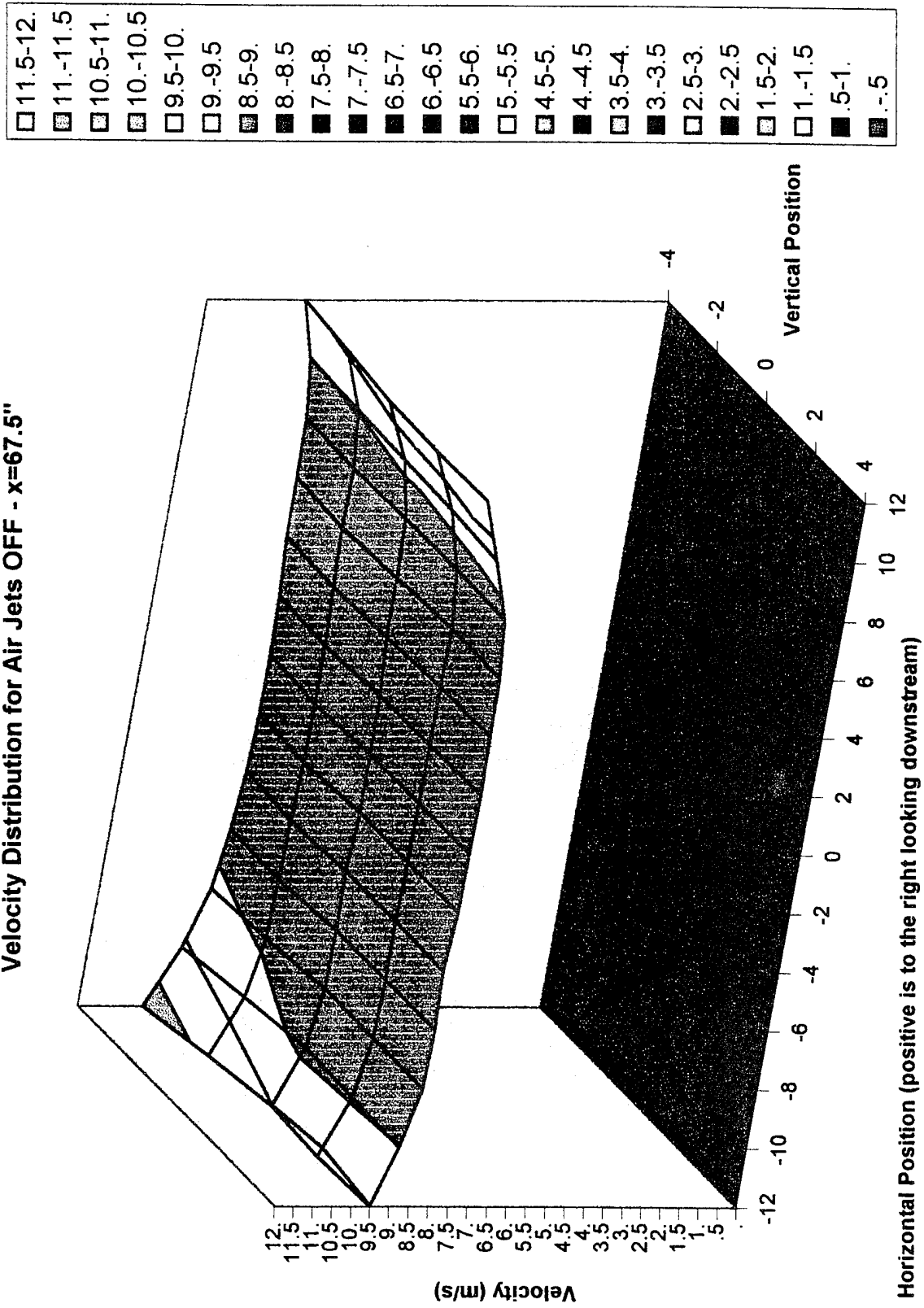
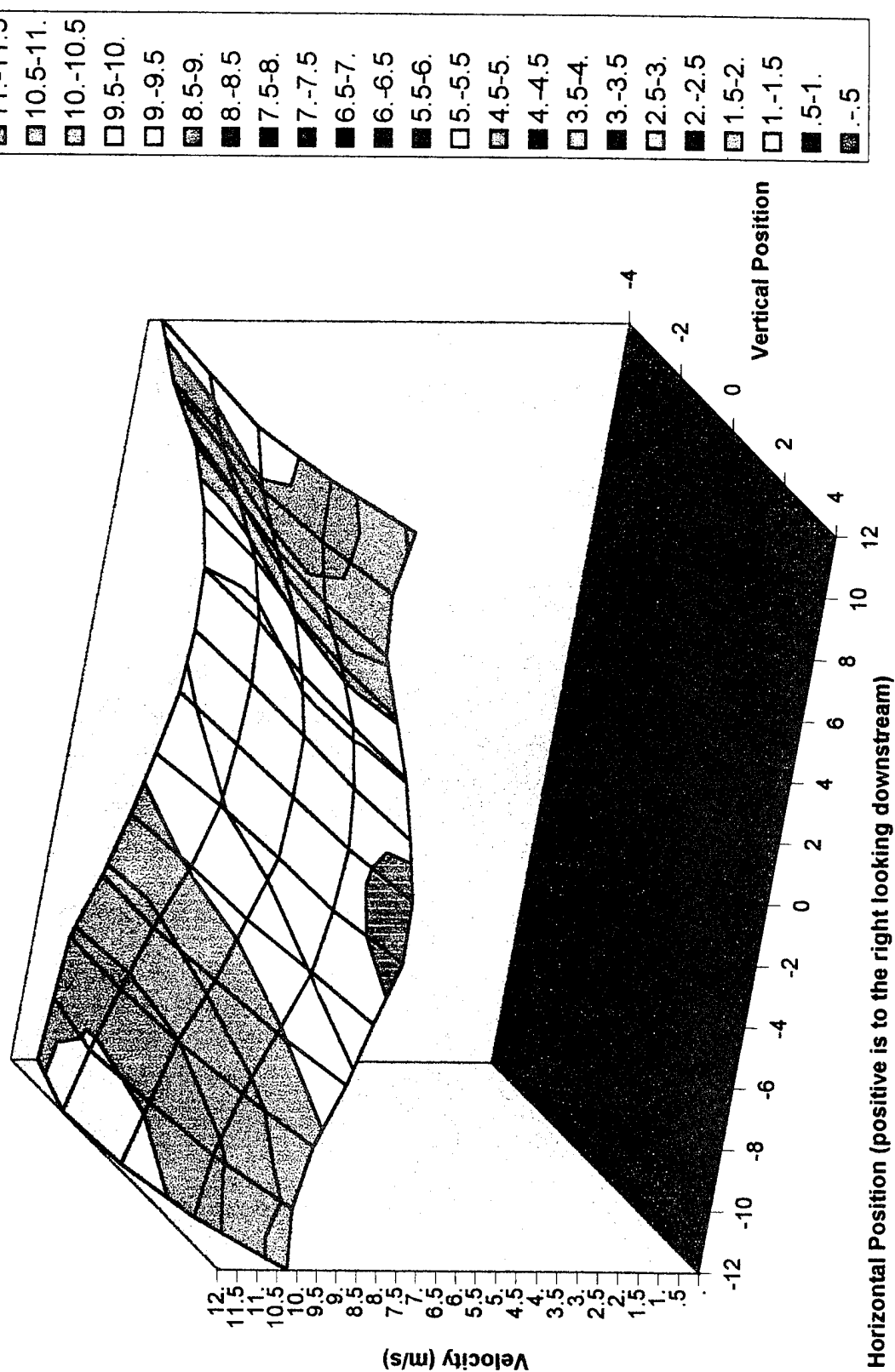


Chart2

Velocity Distribution for Air Jets ON - x=67.5"



## **APPENDIX D**

### Turbulence Intensity Traverse Plots

Chart3

Turbulence Intensity with Air Jets OFF - x=32"

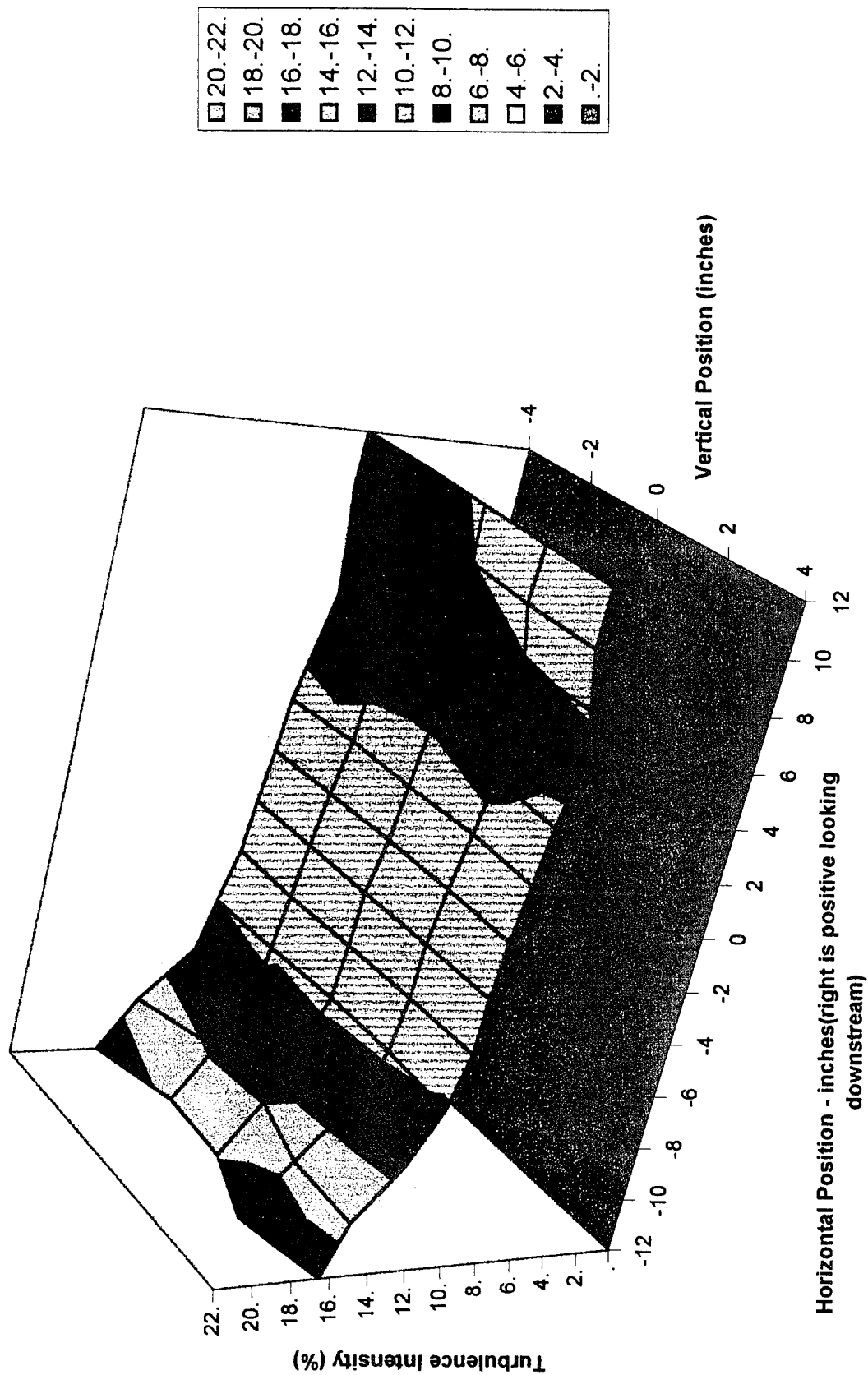




Chart3

Turbulence Intensity with Air Jets ON - x=32"

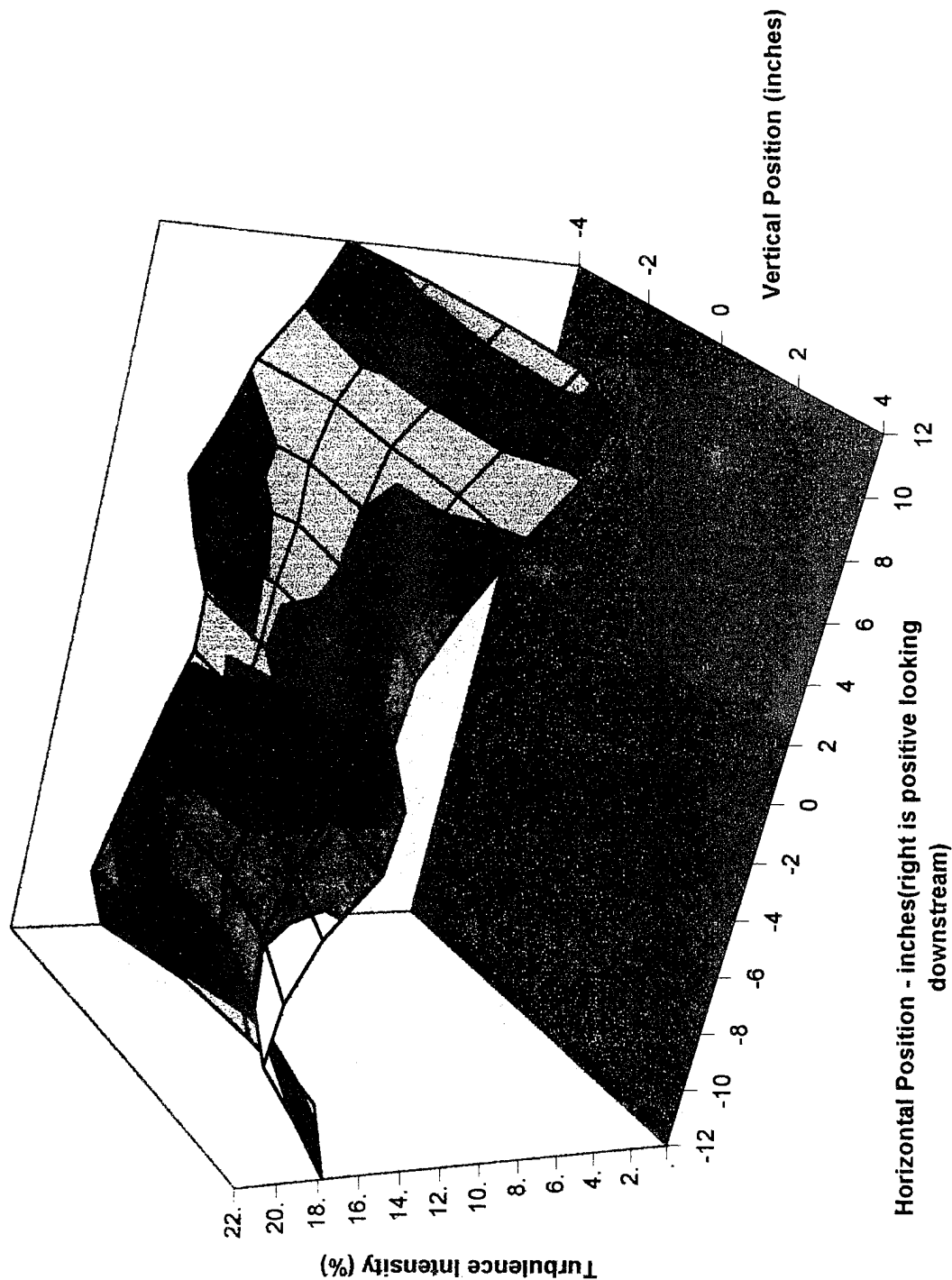


Chart3

Turbulence Intensity with Air Jets OFF - x=35.75"

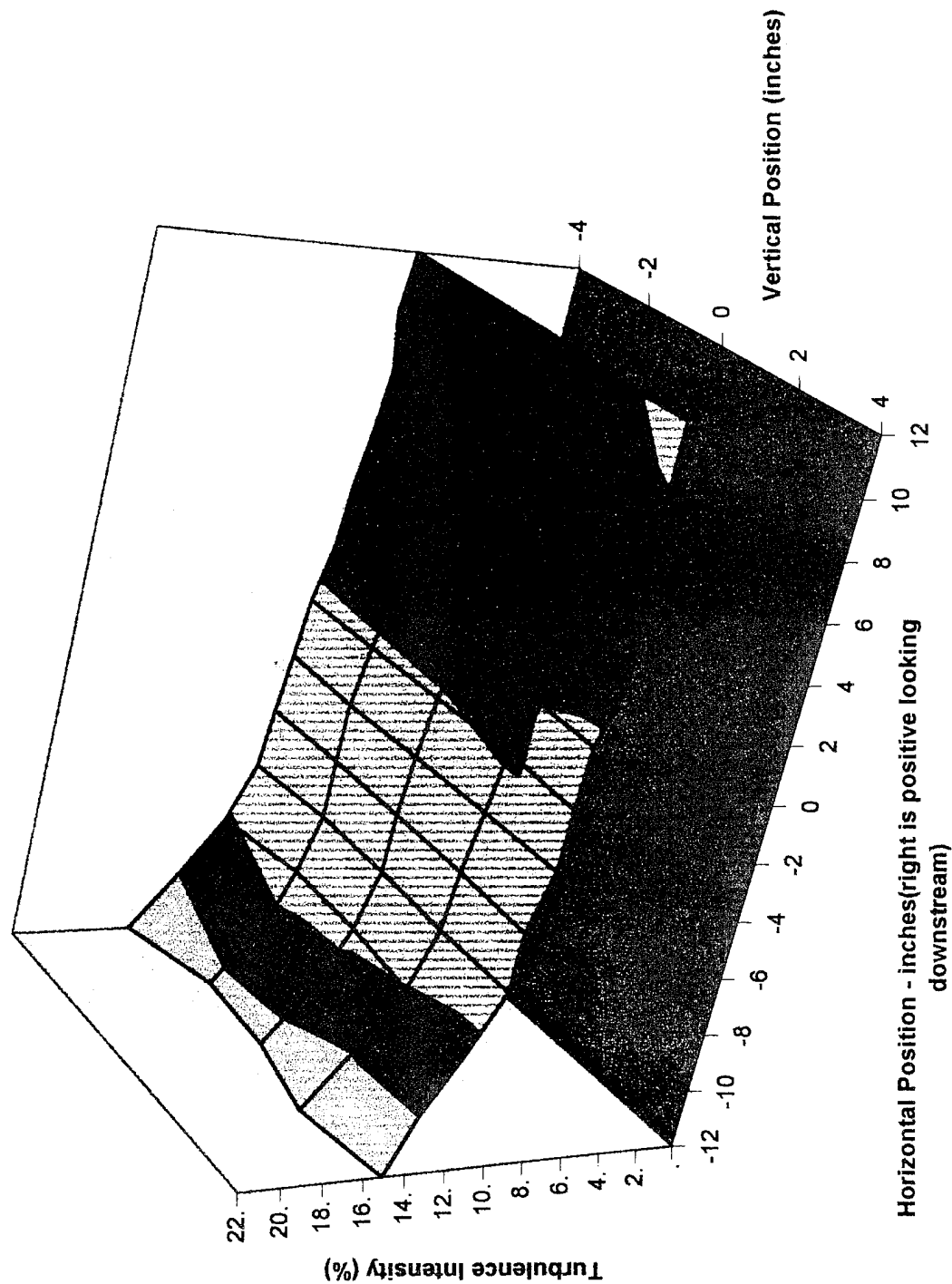
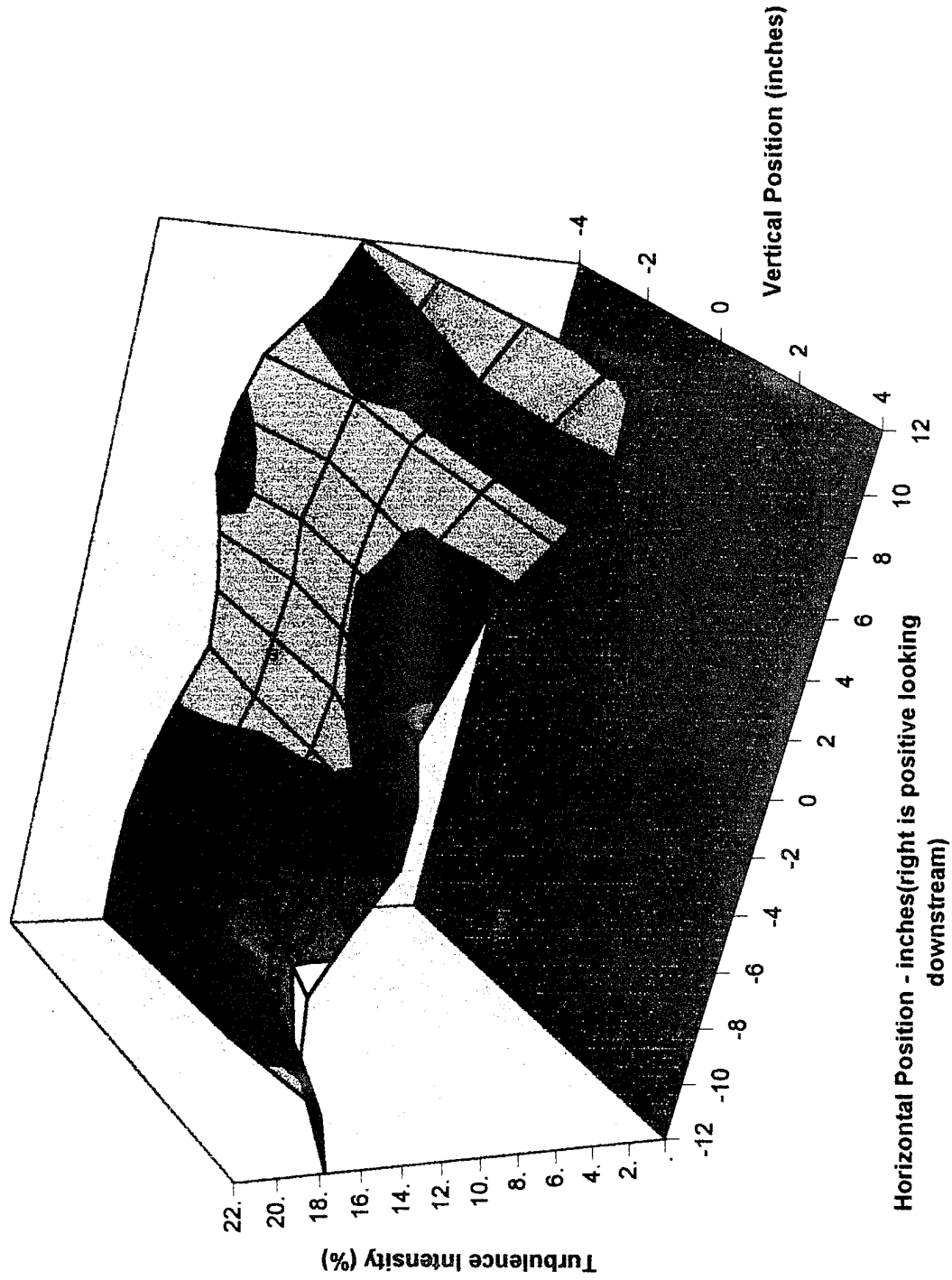


Chart3

Turbulence Intensity with Air Jets ON - x=35.75"



# Turbulence Intensity with Air Jets OFF - x=40"

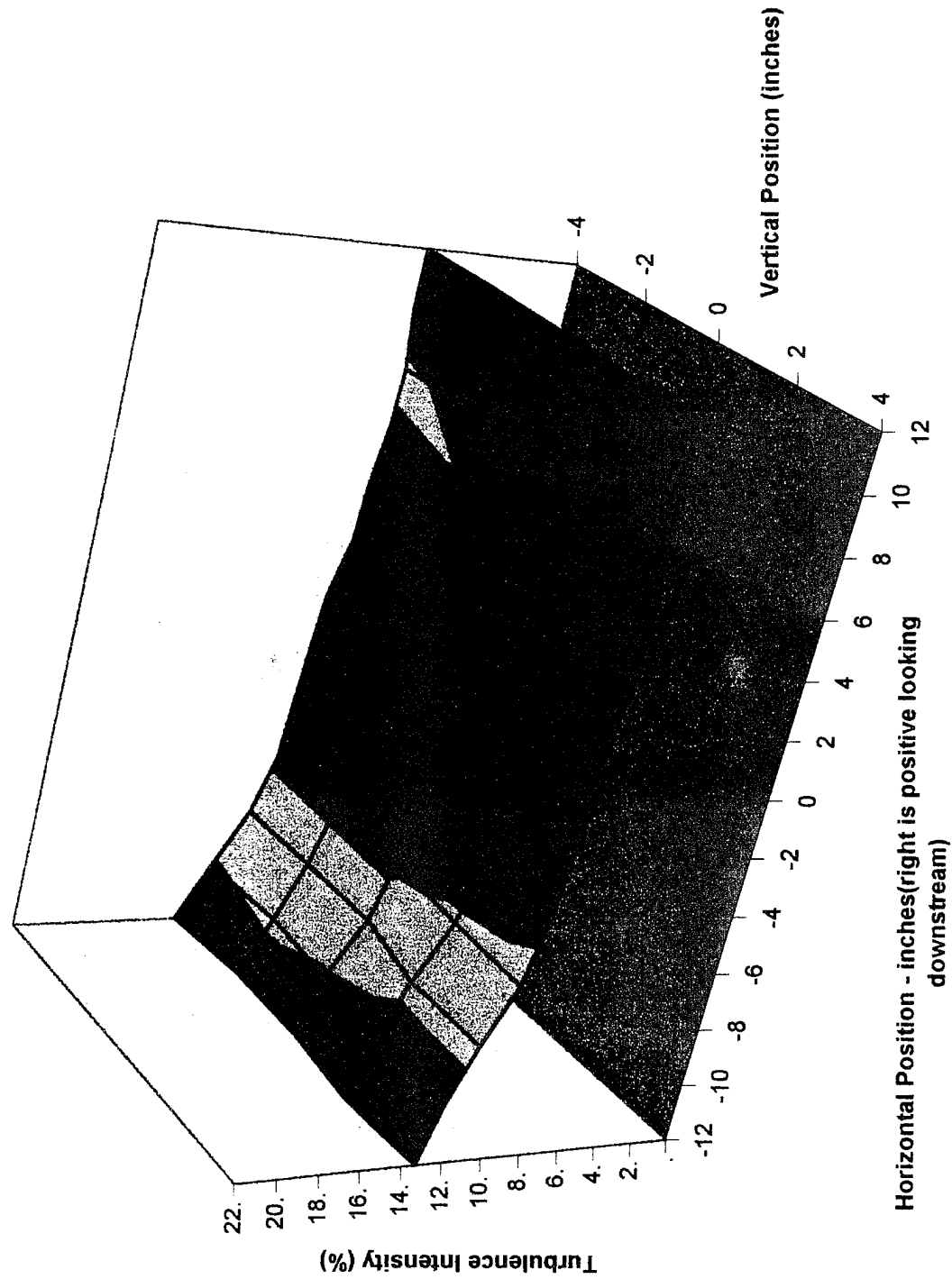
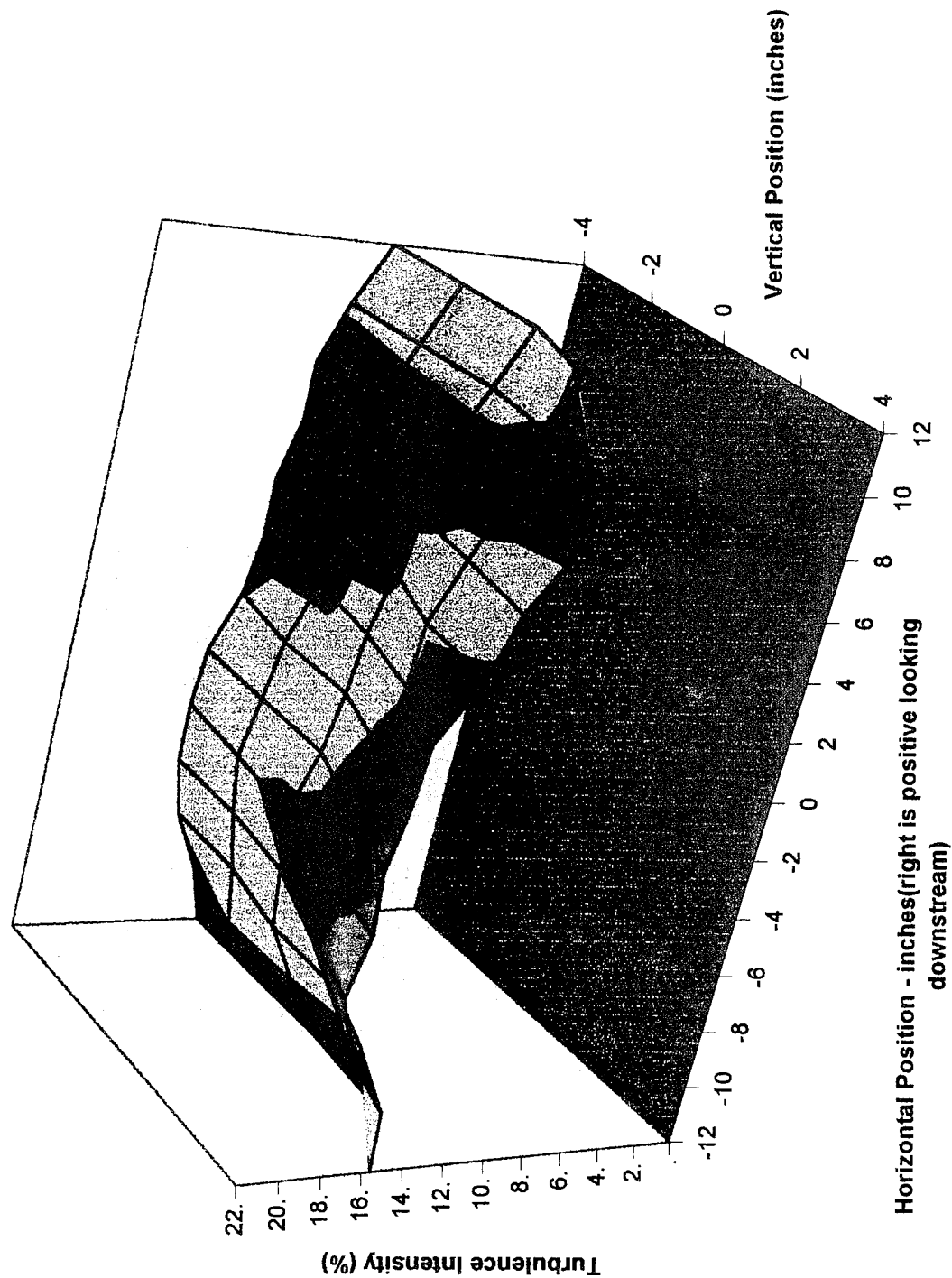


Chart3

Turbulence Intensity with Air Jets ON - x=40"



Turbulence Intensity with Air Jets OFF - x=45.5"

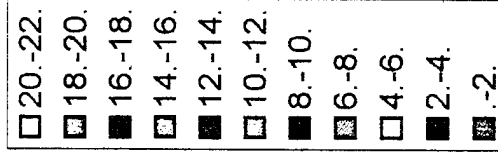
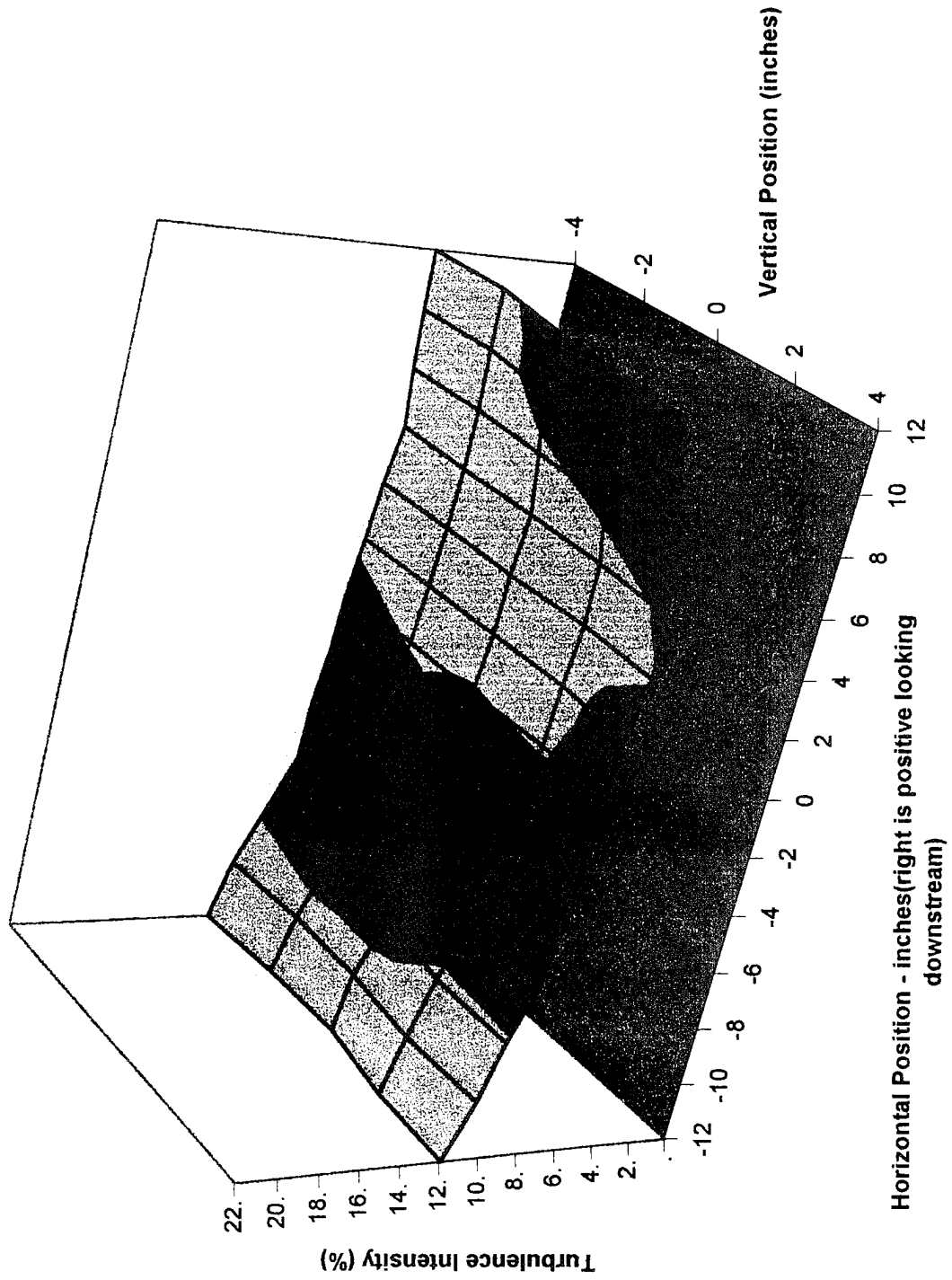


Chart3

Turbulence Intensity with Air Jets OFF - x=52"

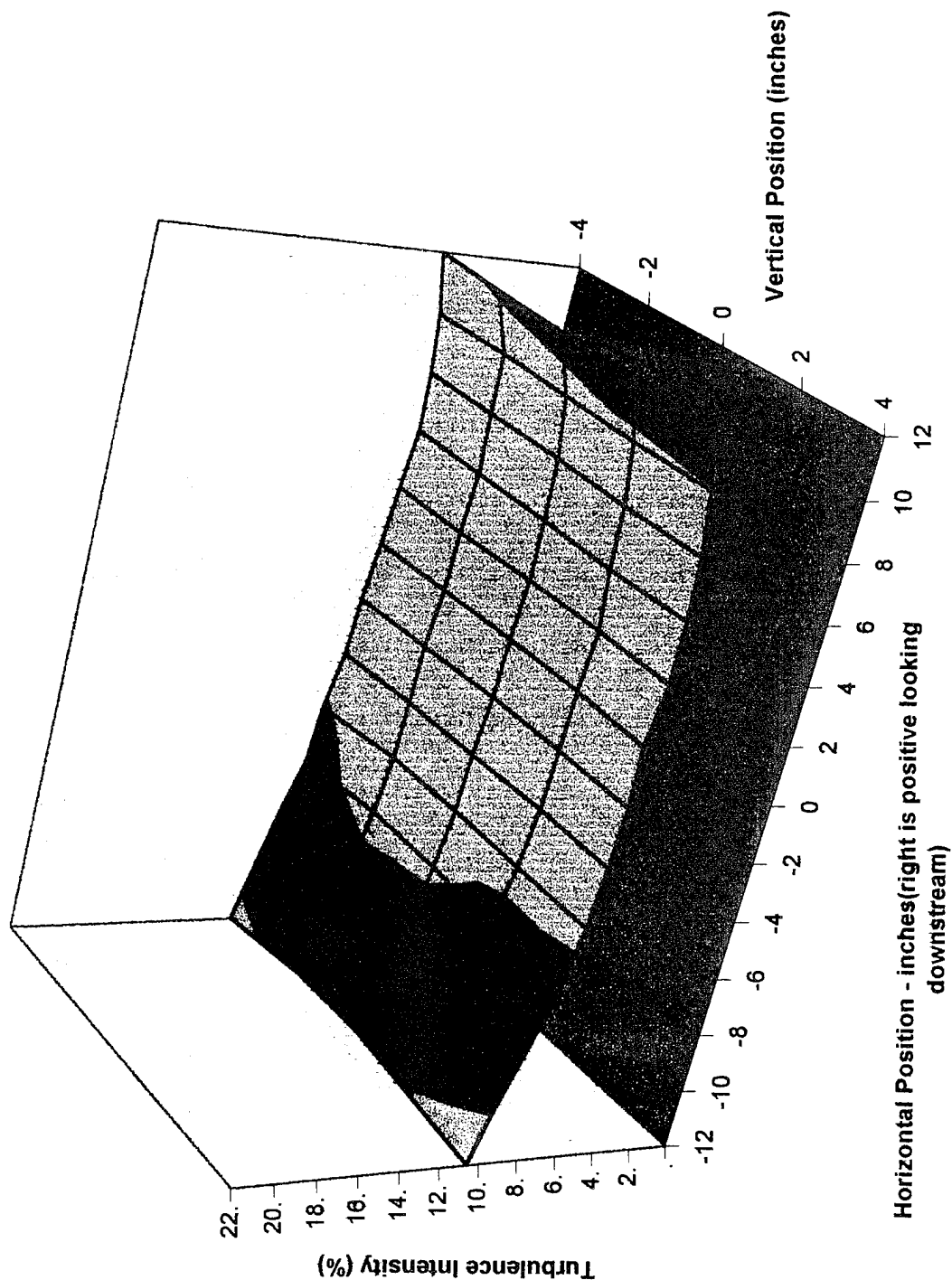


Chart3

Turbulence Intensity with Air Jets ON - x=52"

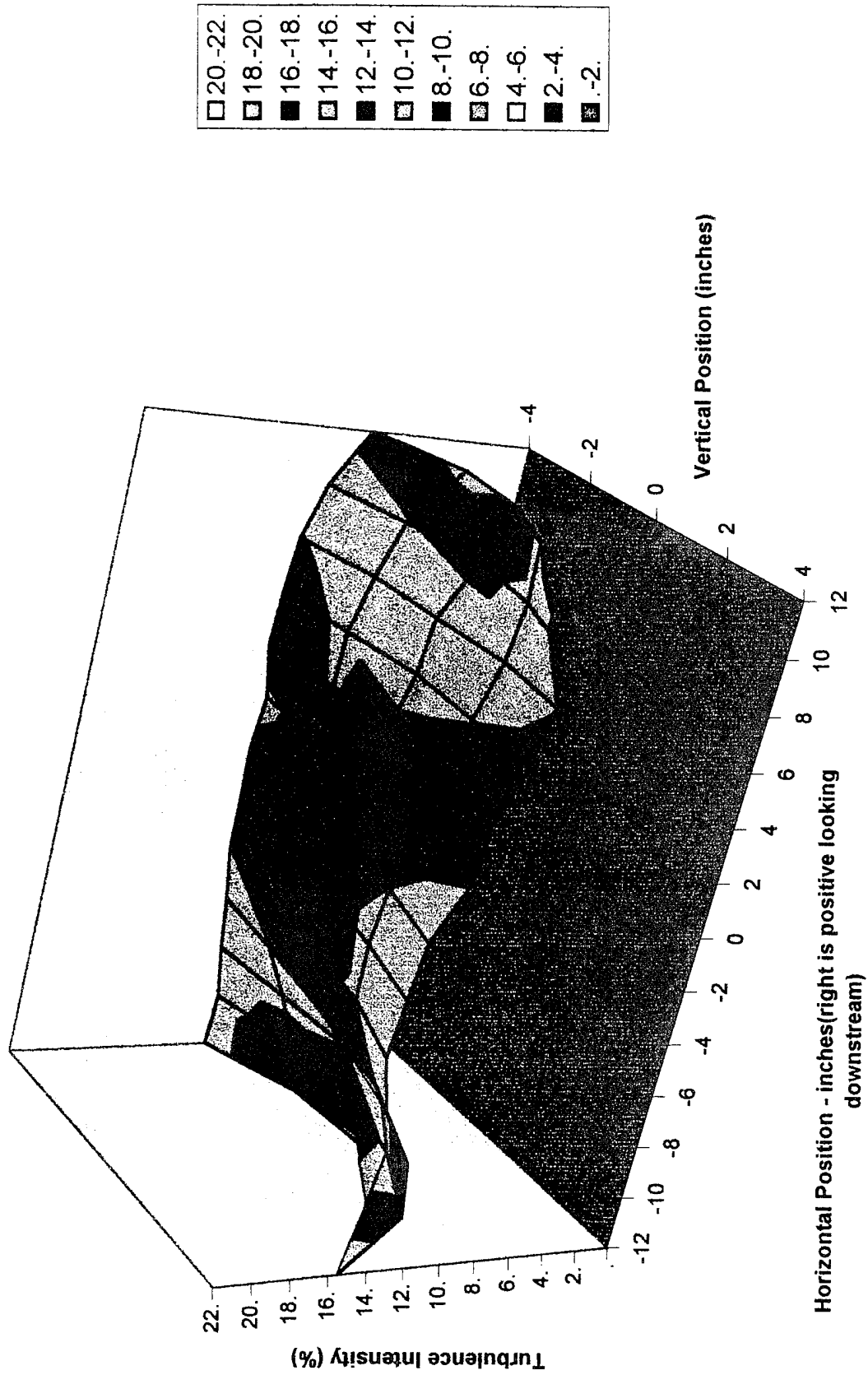




Chart3

Turbulence Intensity with Air Jets OFF - x=67.5"

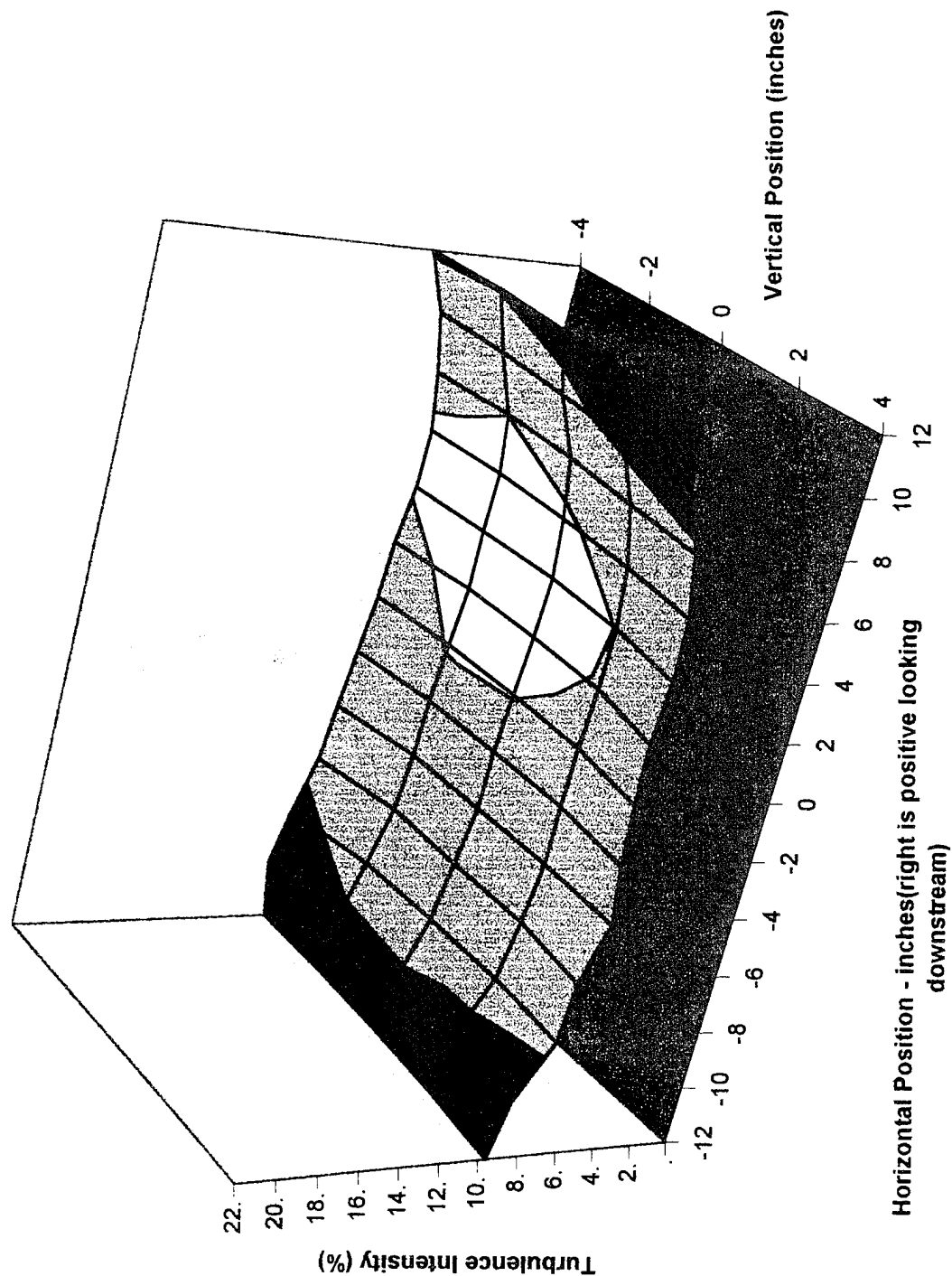
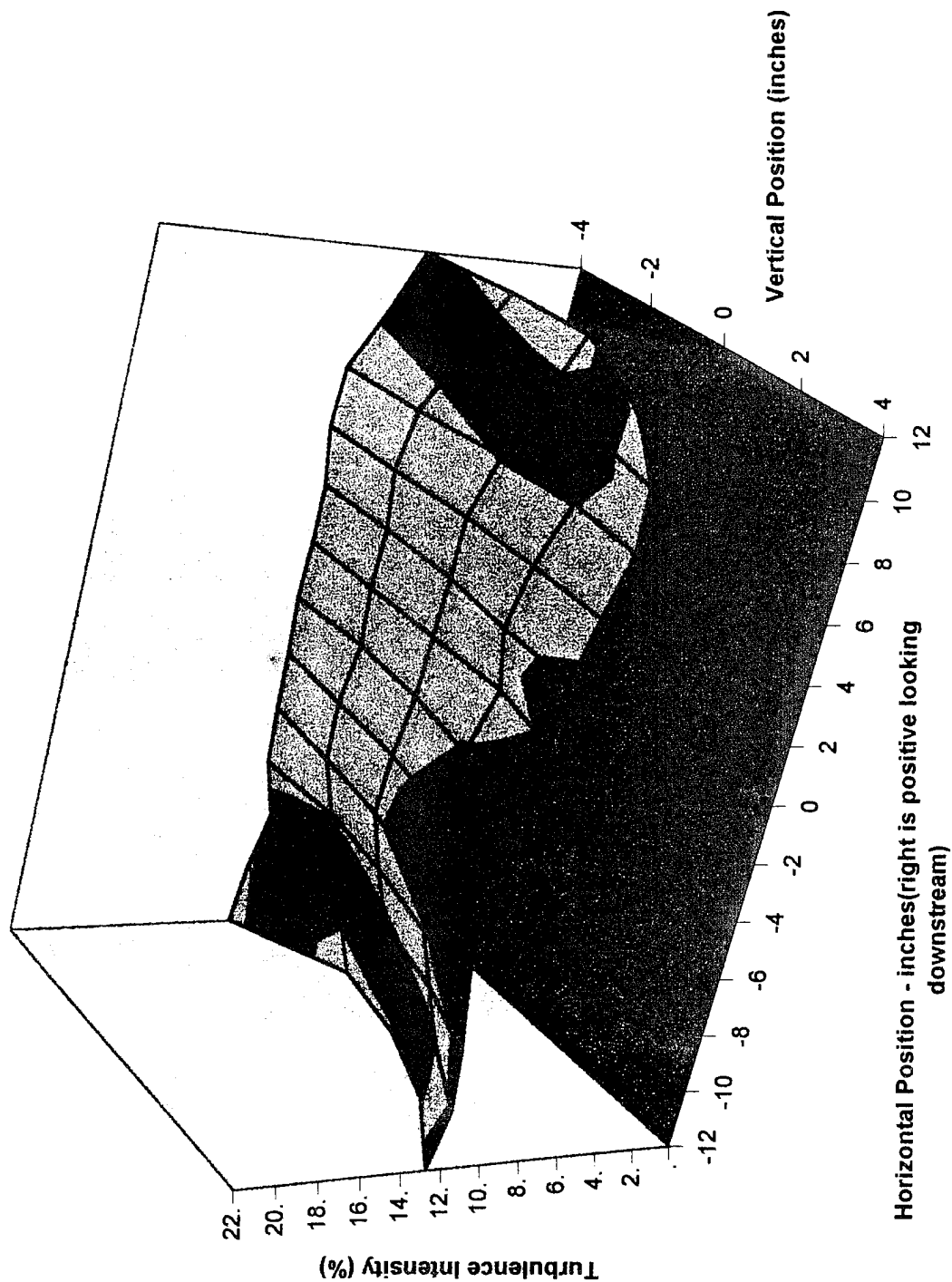


Chart3

Turbulence Intensity with Air Jets ON - x=67.5"



## **APPENDIX E**

### Pitot Tube vs Hot Wire Comparisons

Comparison of Velocities Measured by Pitot and Hot Wire  
with Air Jets OFF at Tunnel Mid-span - x=32"

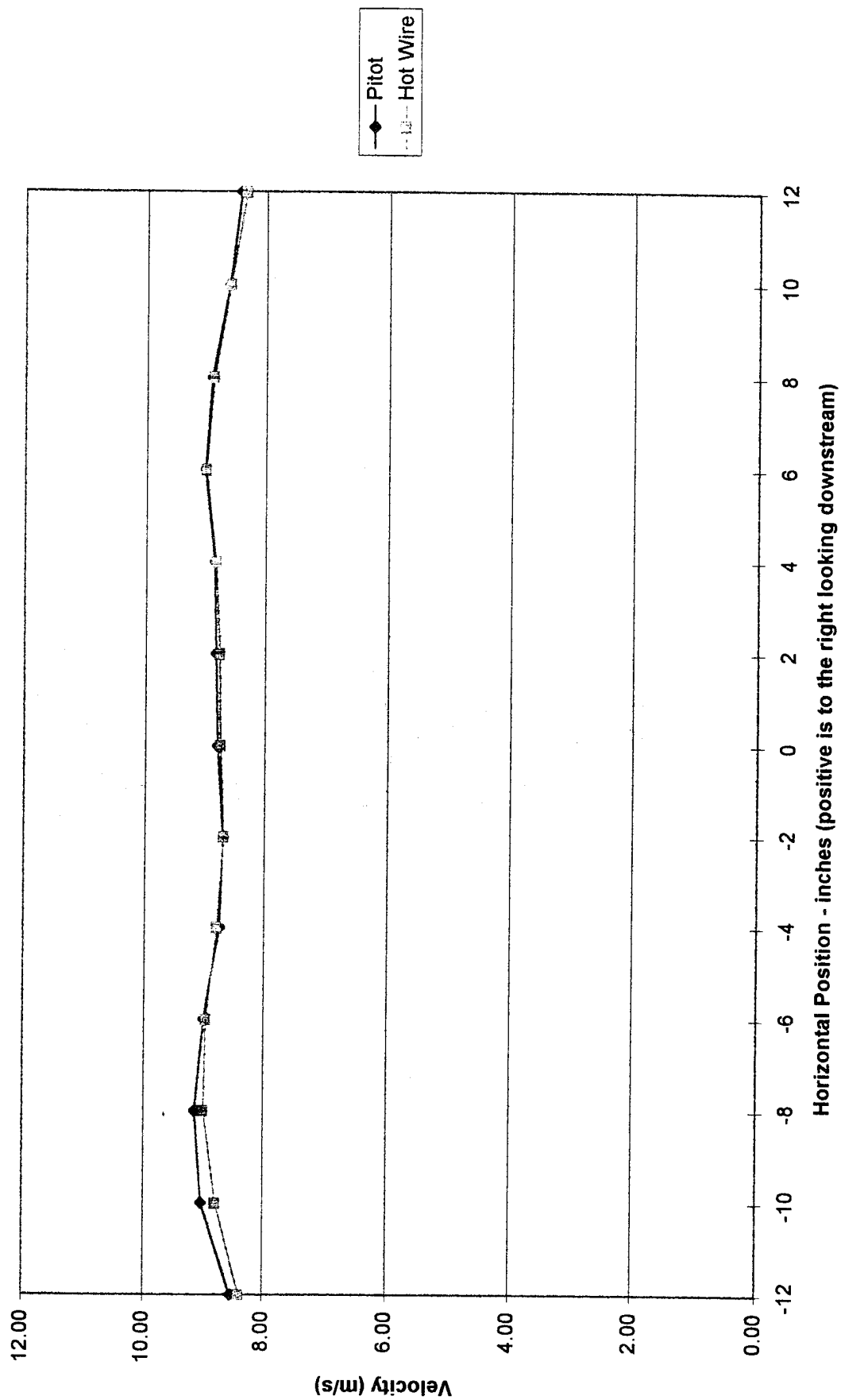


Chart4

Comparison of Velocities Measured by Pitot and Hot Wire  
with Air Jets ON at Tunnel Mid-span -  $x=32''$

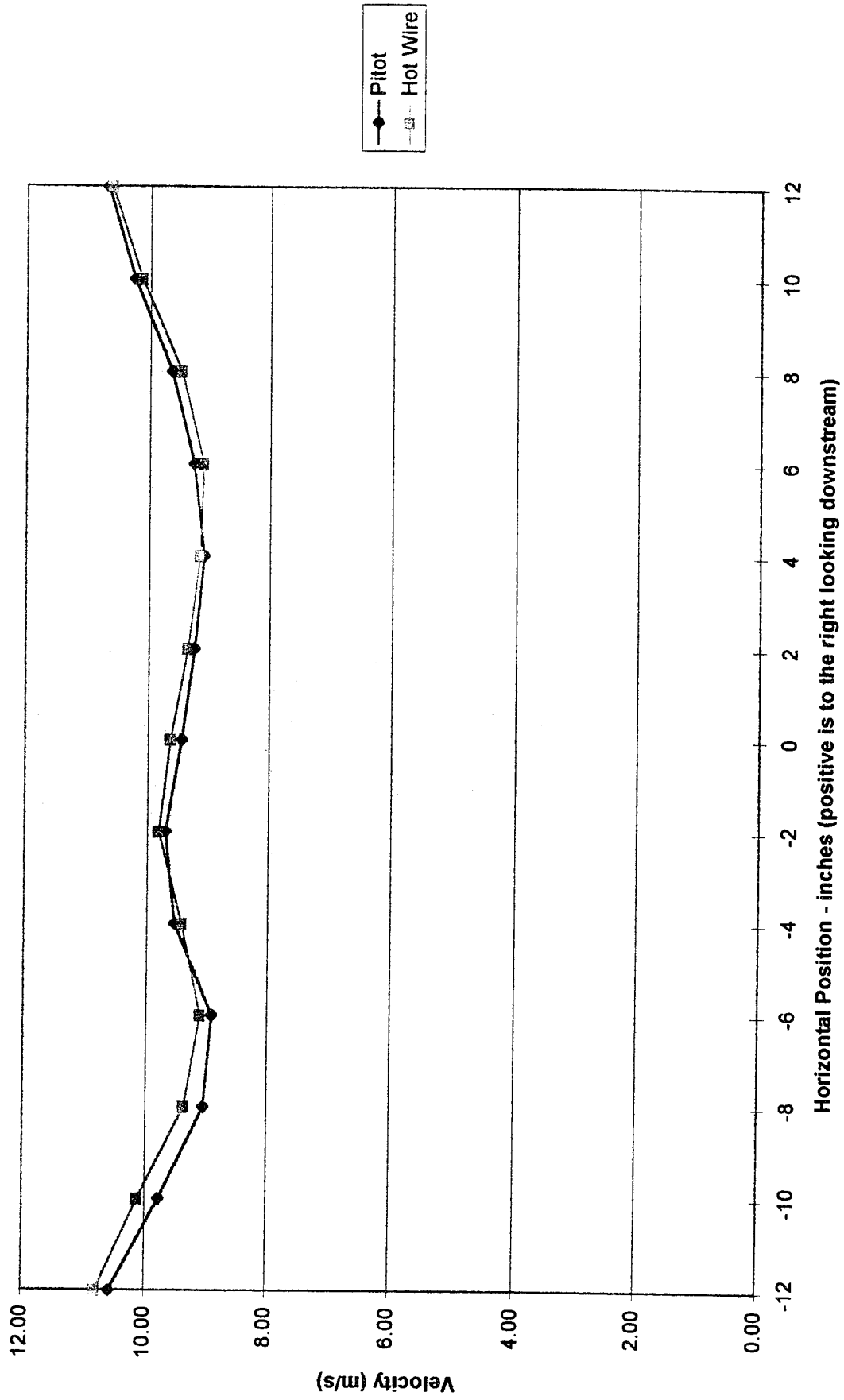


Chart4

Comparison of Velocities Measured by Pitot and Hot Wire  
with Air Jets OFF at Tunnel Mid-span - x=35.75"

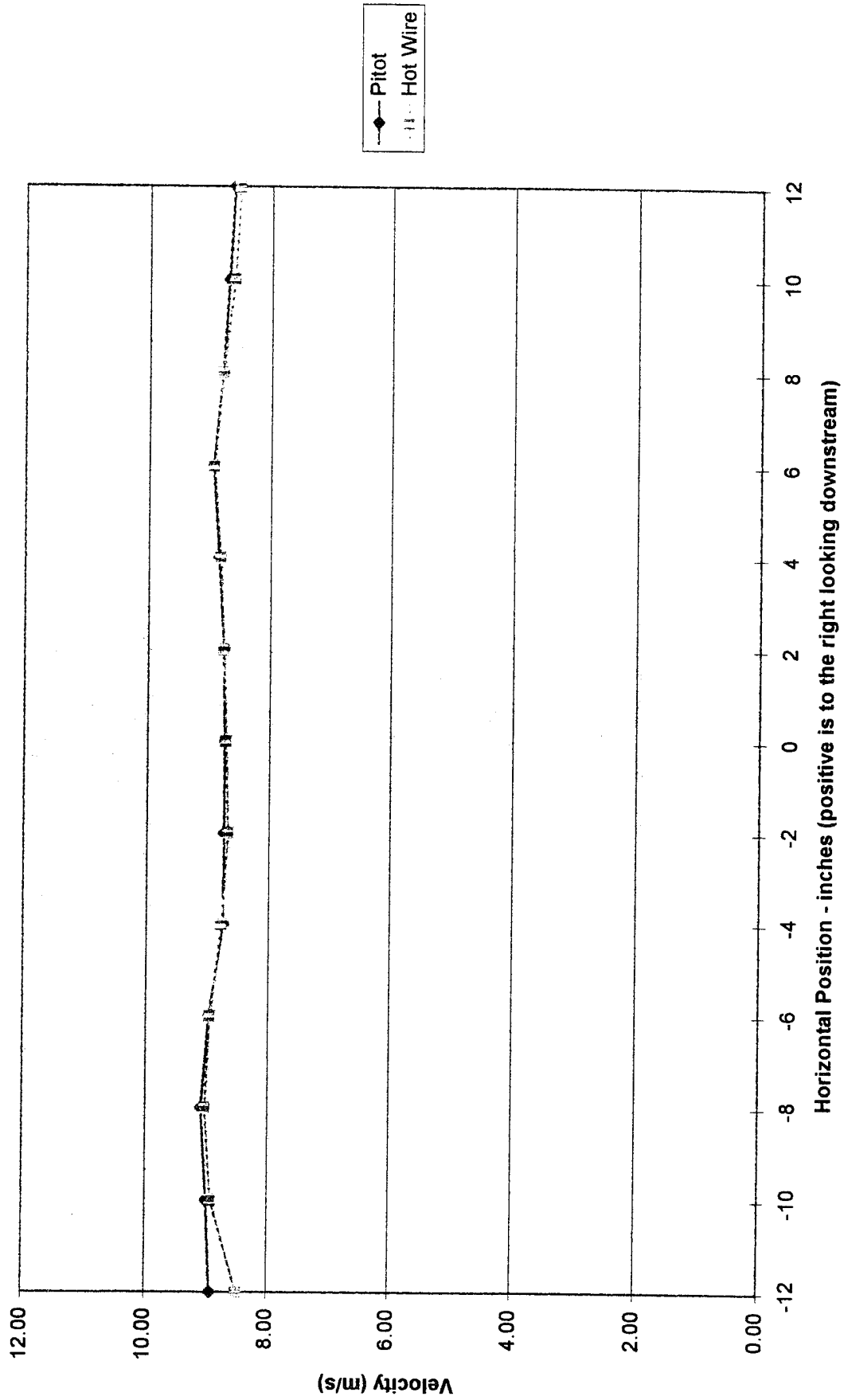


Chart4

Comparison of Velocities Measured by Pitot and Hot Wire  
with Air Jets ON at Tunnel Mid-span -  $x=35.75''$

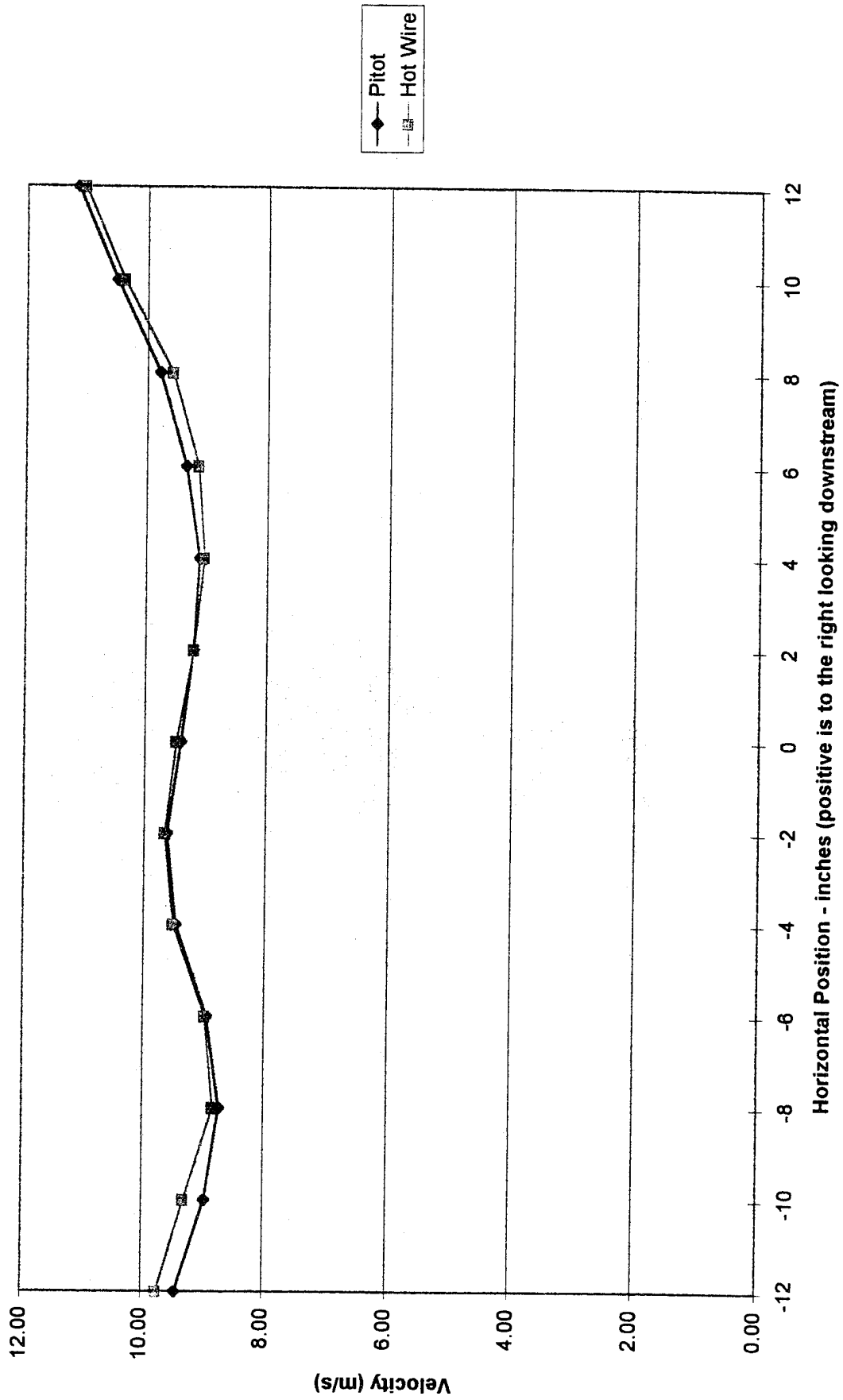


Chart4

**Comparison of Velocities Measured by Pitot and Hot Wire  
with Air Jets OFF at Tunnel Mid-span - x=40"**

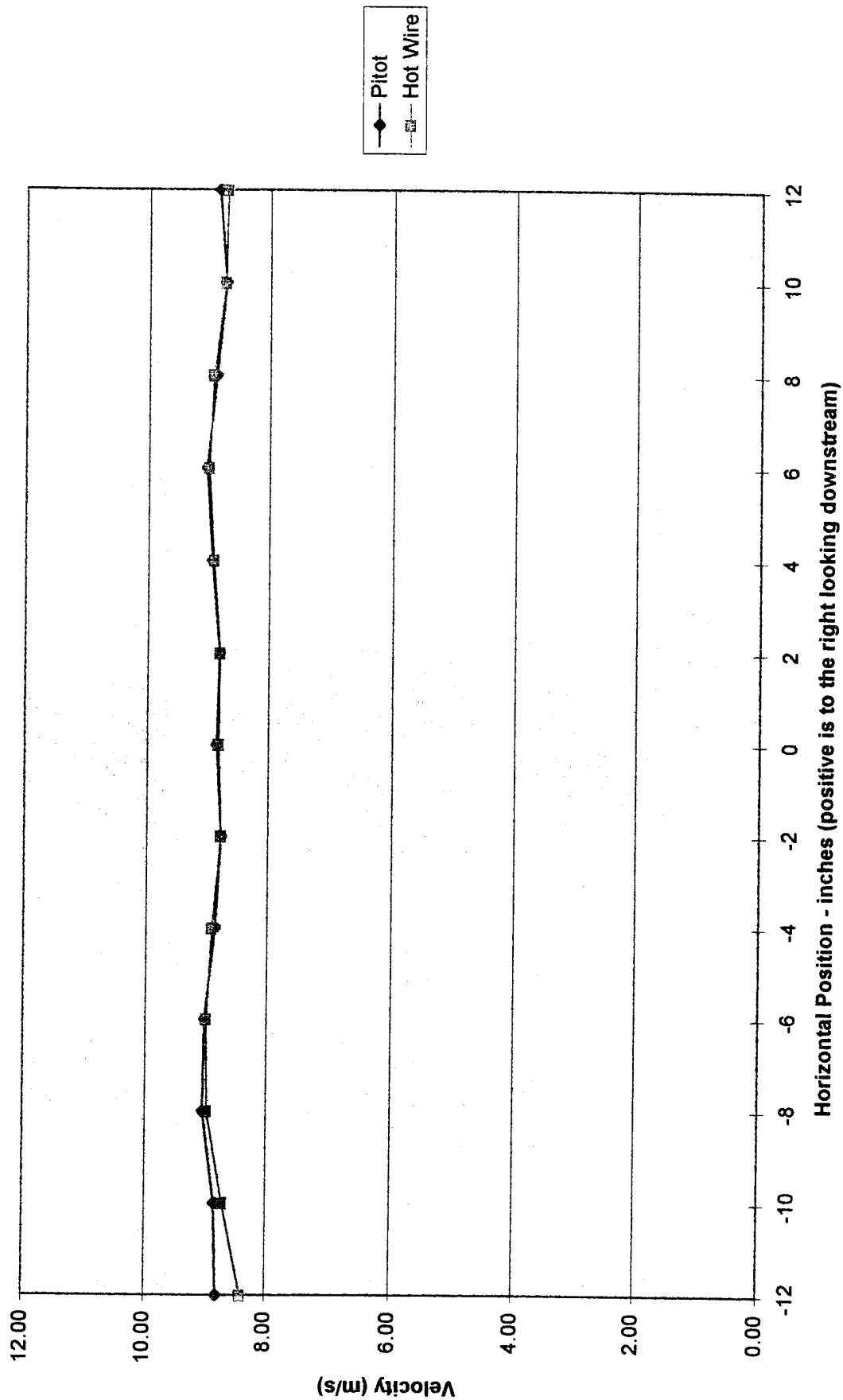




Chart4

Comparison of Velocities Measured by Pitot and Hot Wire  
with Air Jets ON at Tunnel Mid-span -  $x=40''$

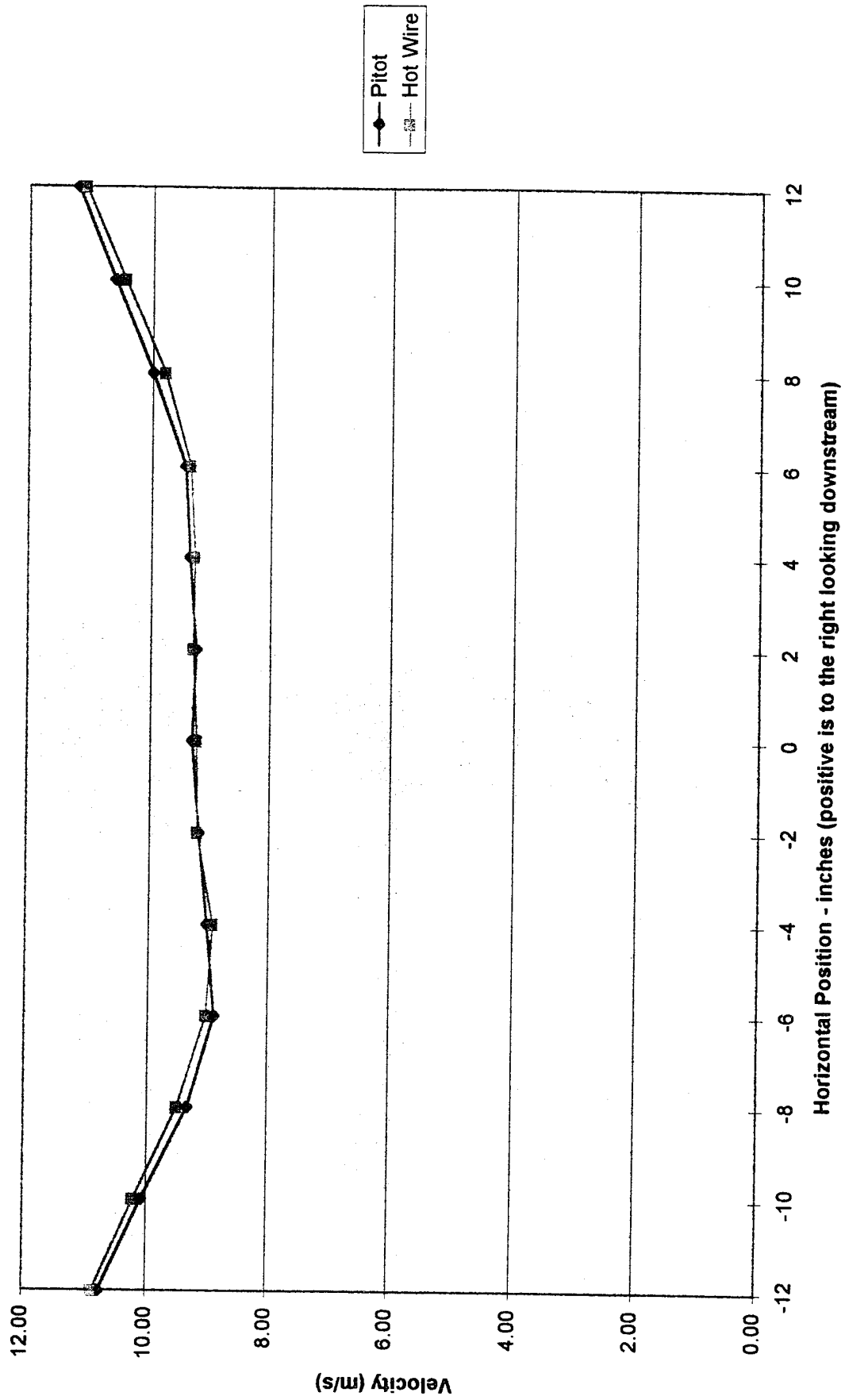


Chart4

**Comparison of Velocities Measured by Pitot and Hot Wire  
with Air Jets OFF at Tunnel Mid-span -  $x=45.5''$**

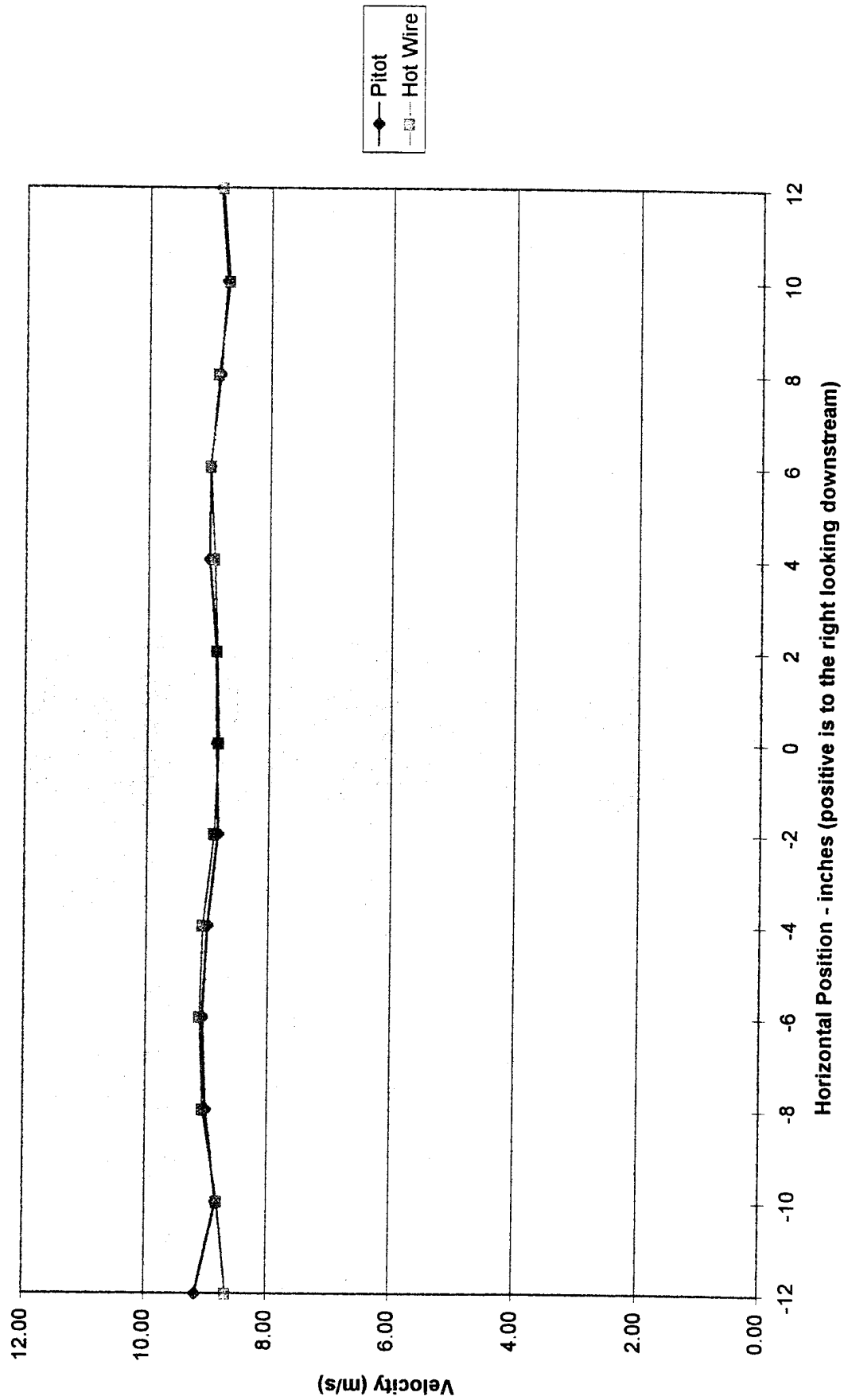


Chart4

**Comparison of Velocities Measured by Pitot and Hot Wire  
with Air Jets OFF at Tunnel Mid-span - x=52"**

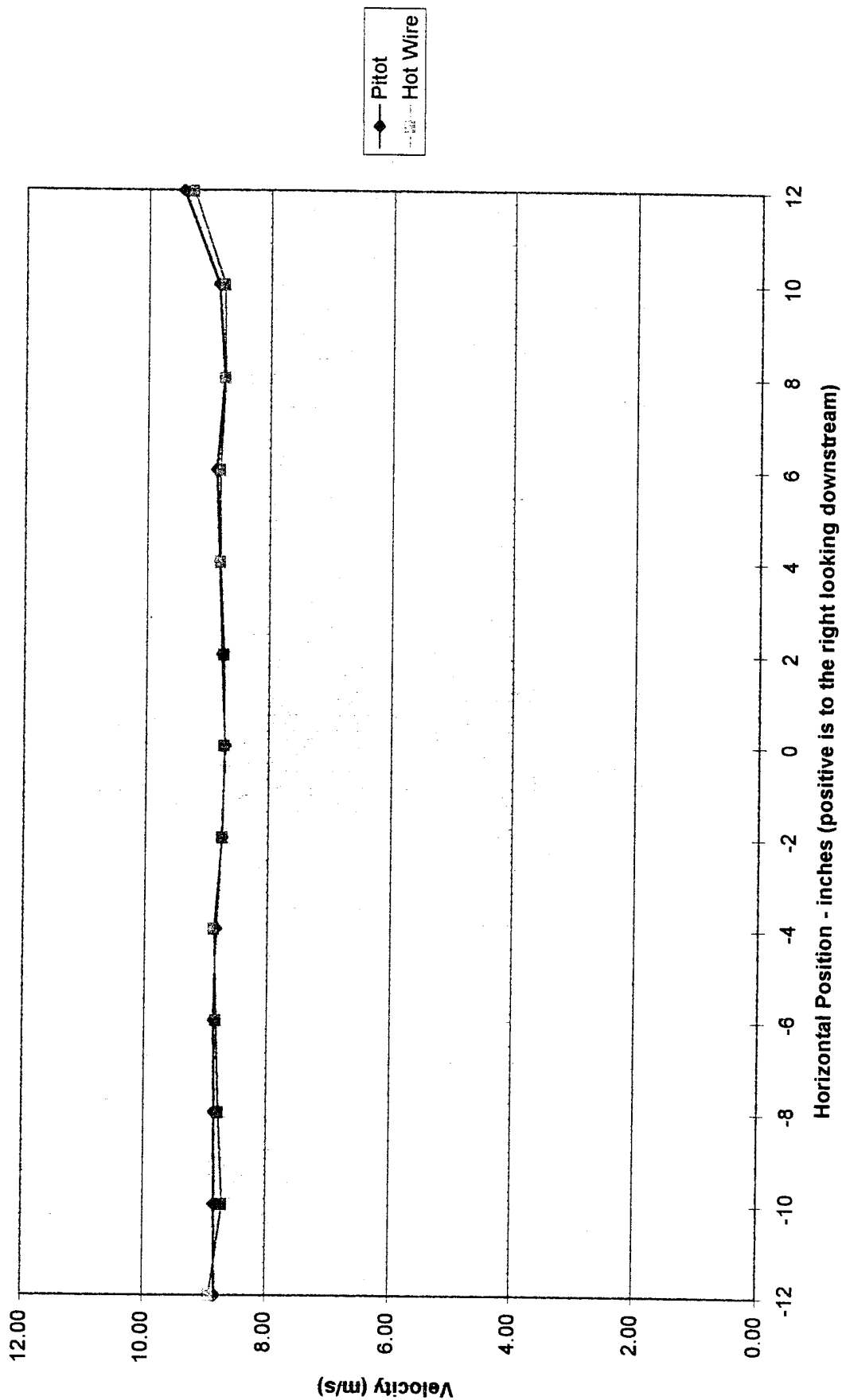


Chart4

Comparison of Velocities Measured by Pitot and Hot Wire  
with Air Jets ON at Tunnel Mid-span - x=52"

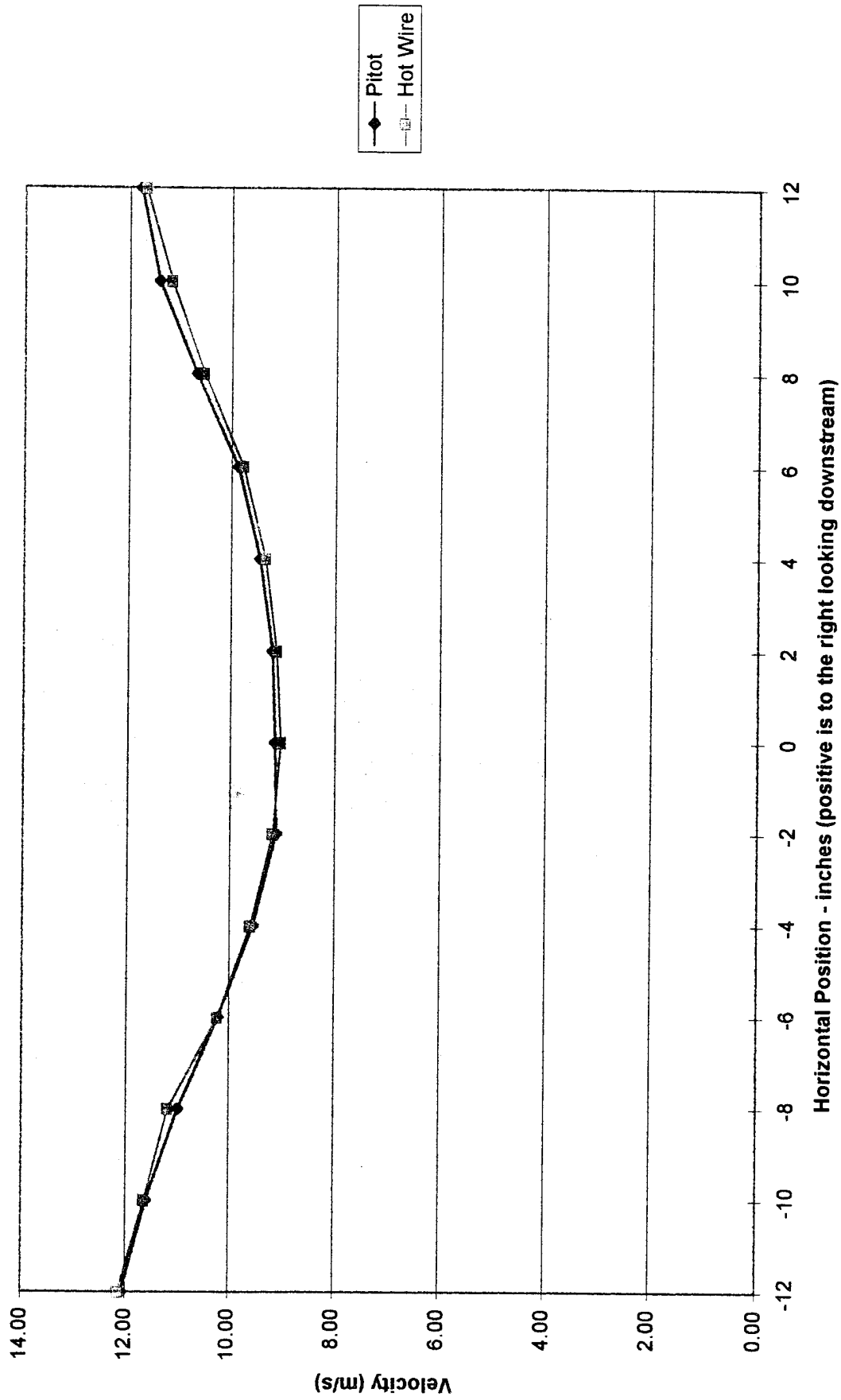


Chart4

Comparison of Velocities Measured by Pitot and Hot Wire  
with Air Jets OFF at Tunnel Mid-span - x=67.5"

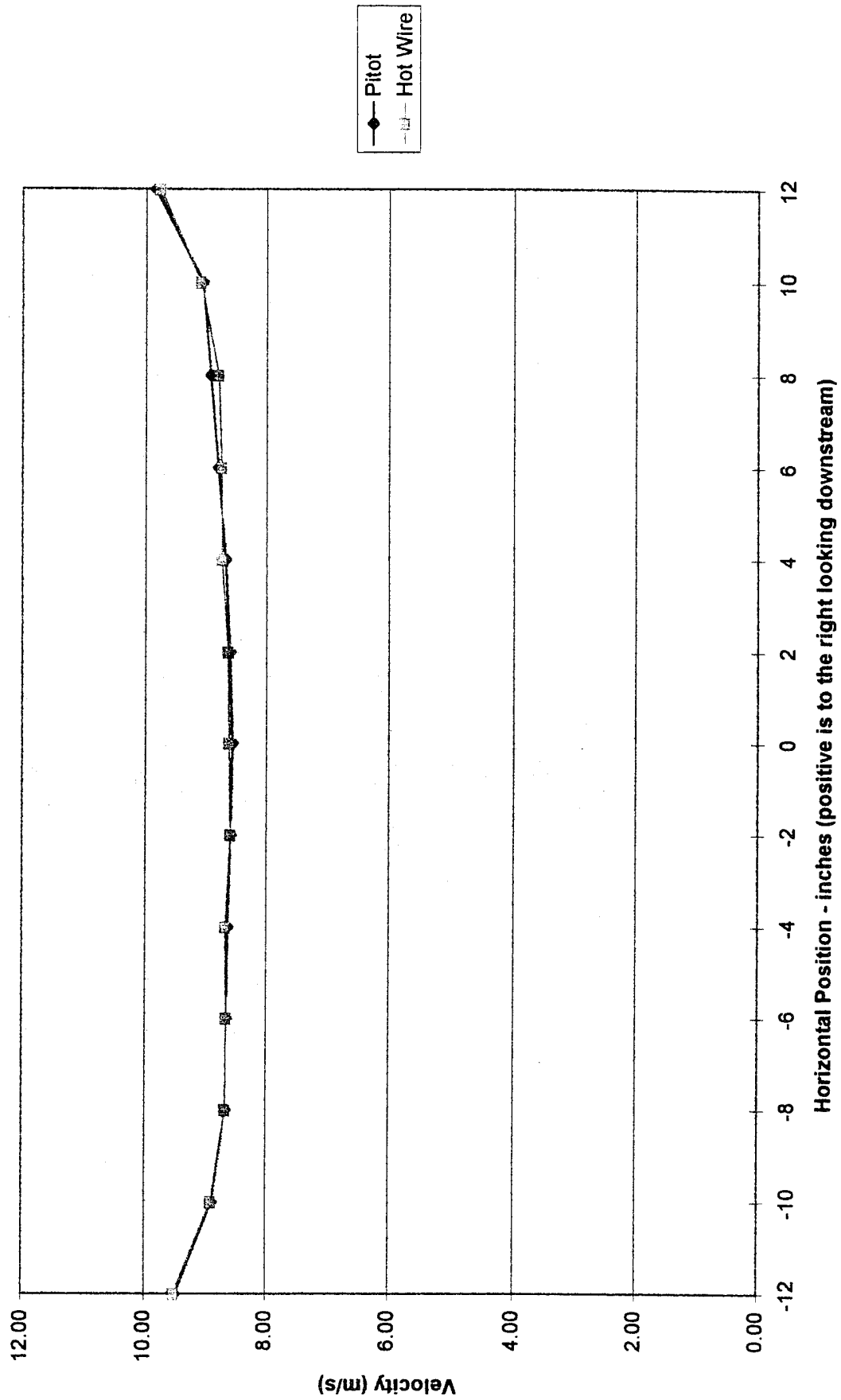
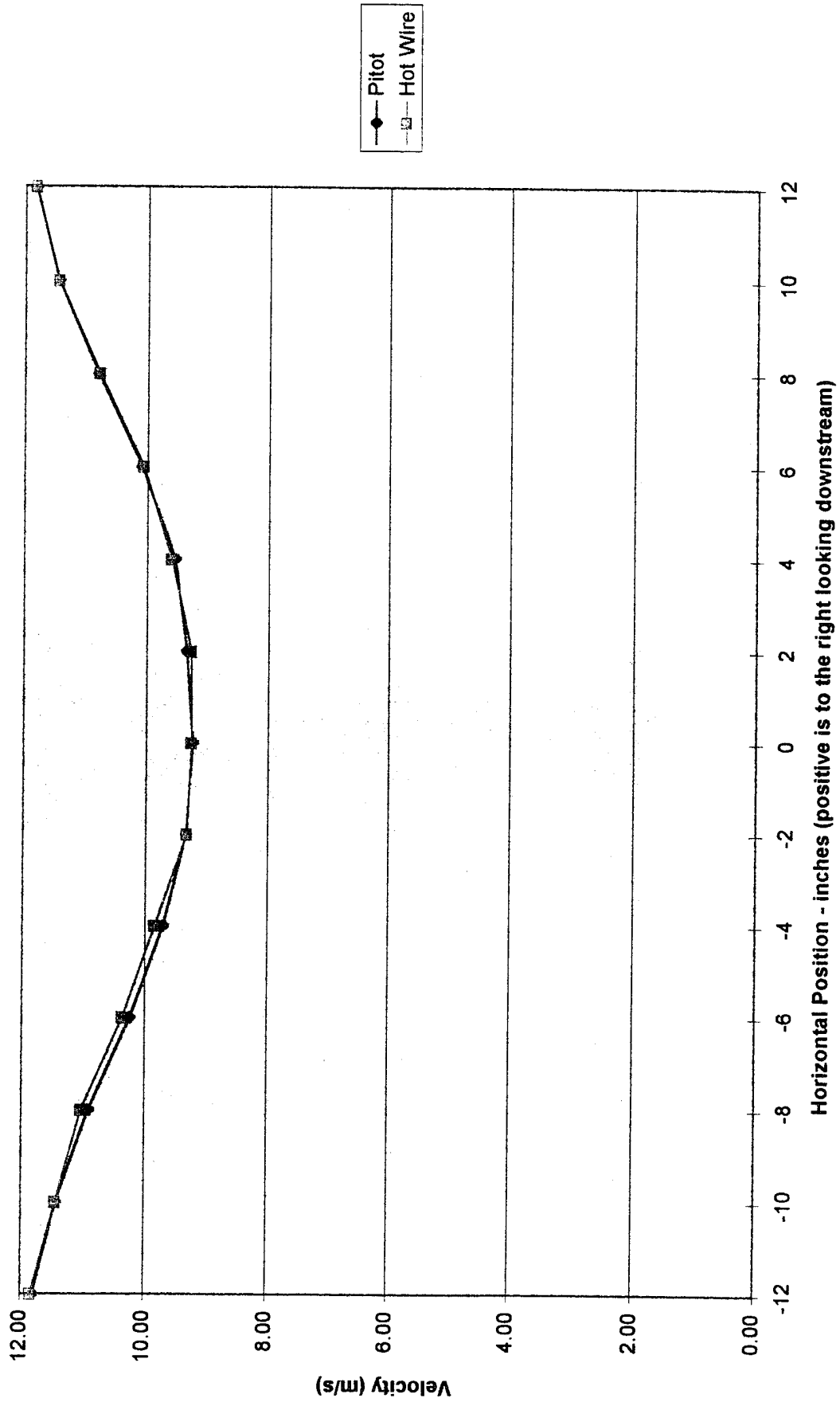


Chart4

Comparison of Velocities Measured by Pitot and Hot Wire  
with Air Jets ON at Tunnel Mid-span - x=67.5" -Sep 1



## APPENDIX F

### Air Jet Induced Turbulence Effects

Chart5

# Effect of Air Jets on Turbulence Intensity - x=32"

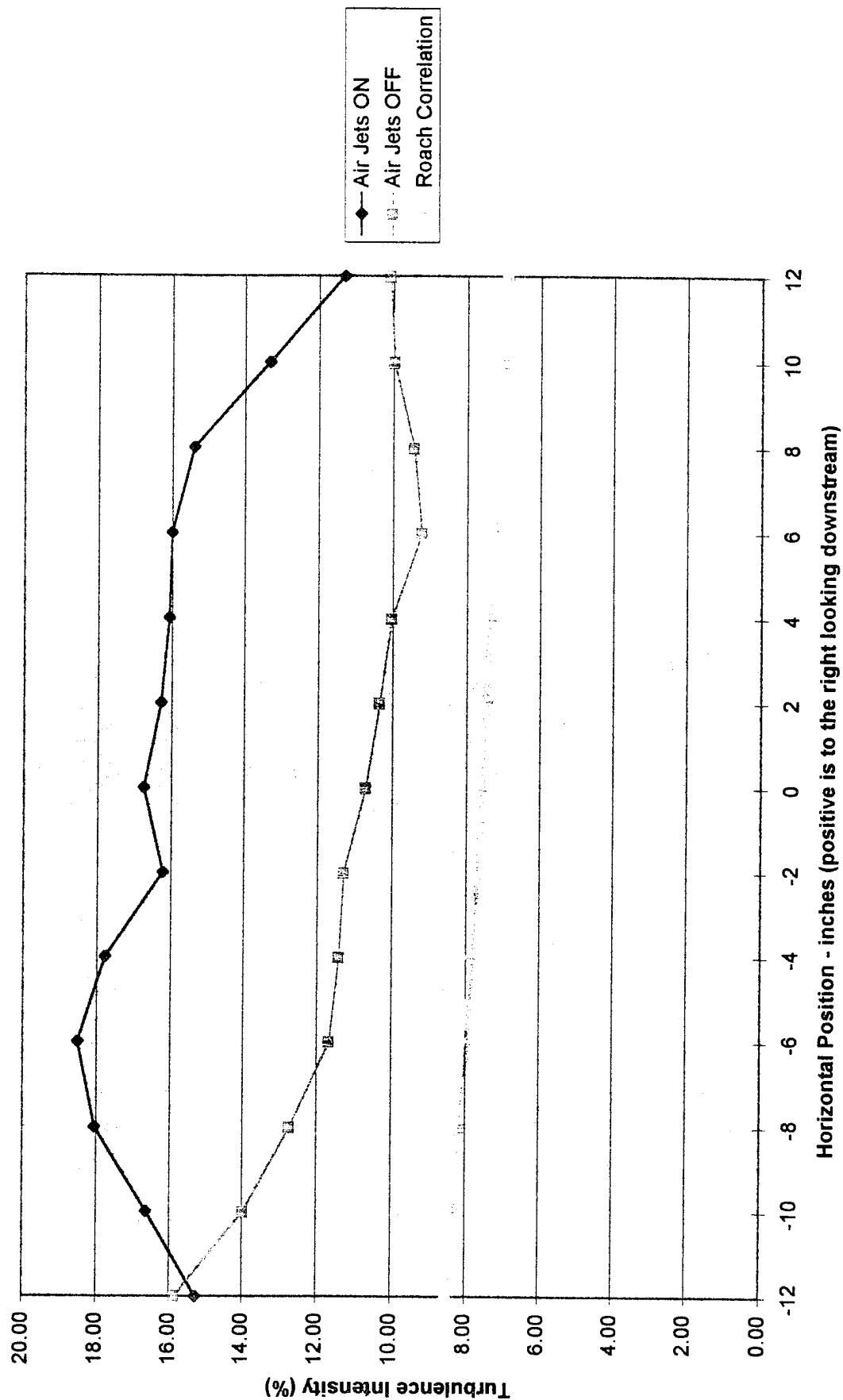




Chart5

Effect of Air Jets on Turbulence Intensity - x=32"

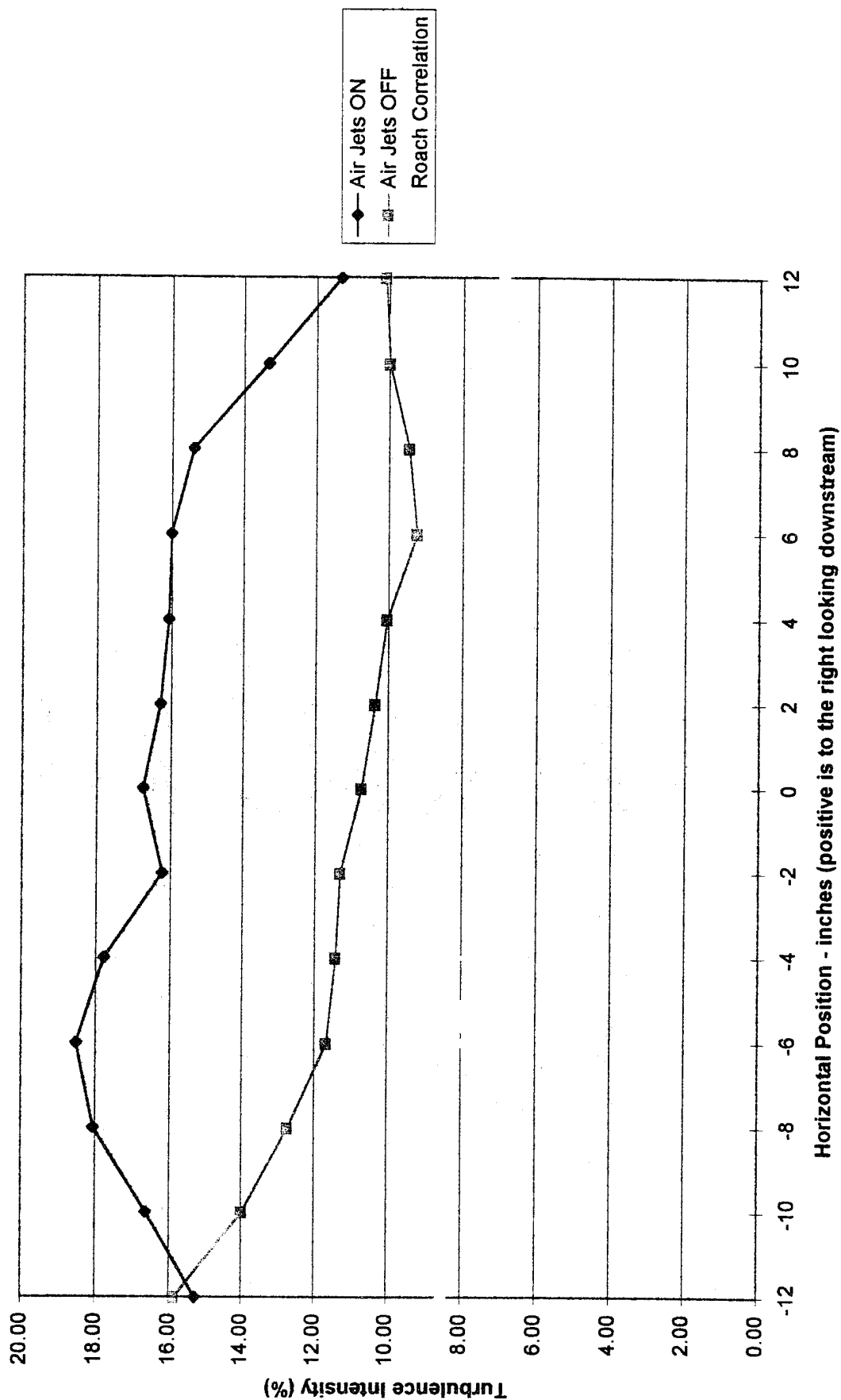


Chart5

Effect of Air Jets on Turbulence Intensity - x=35.75"

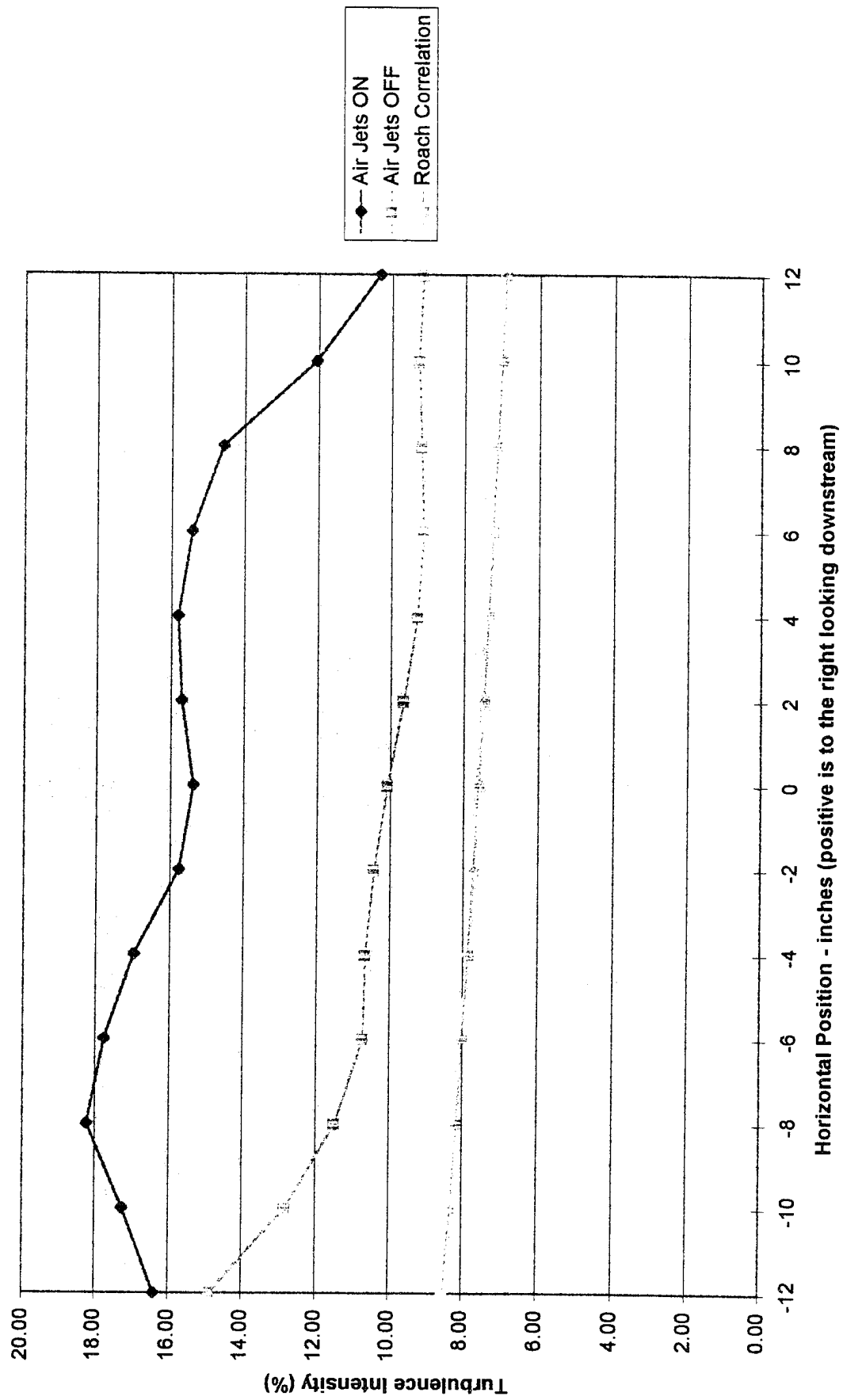


Chart5

Effect of Air Jets on Turbulence Intensity - x=35.75"

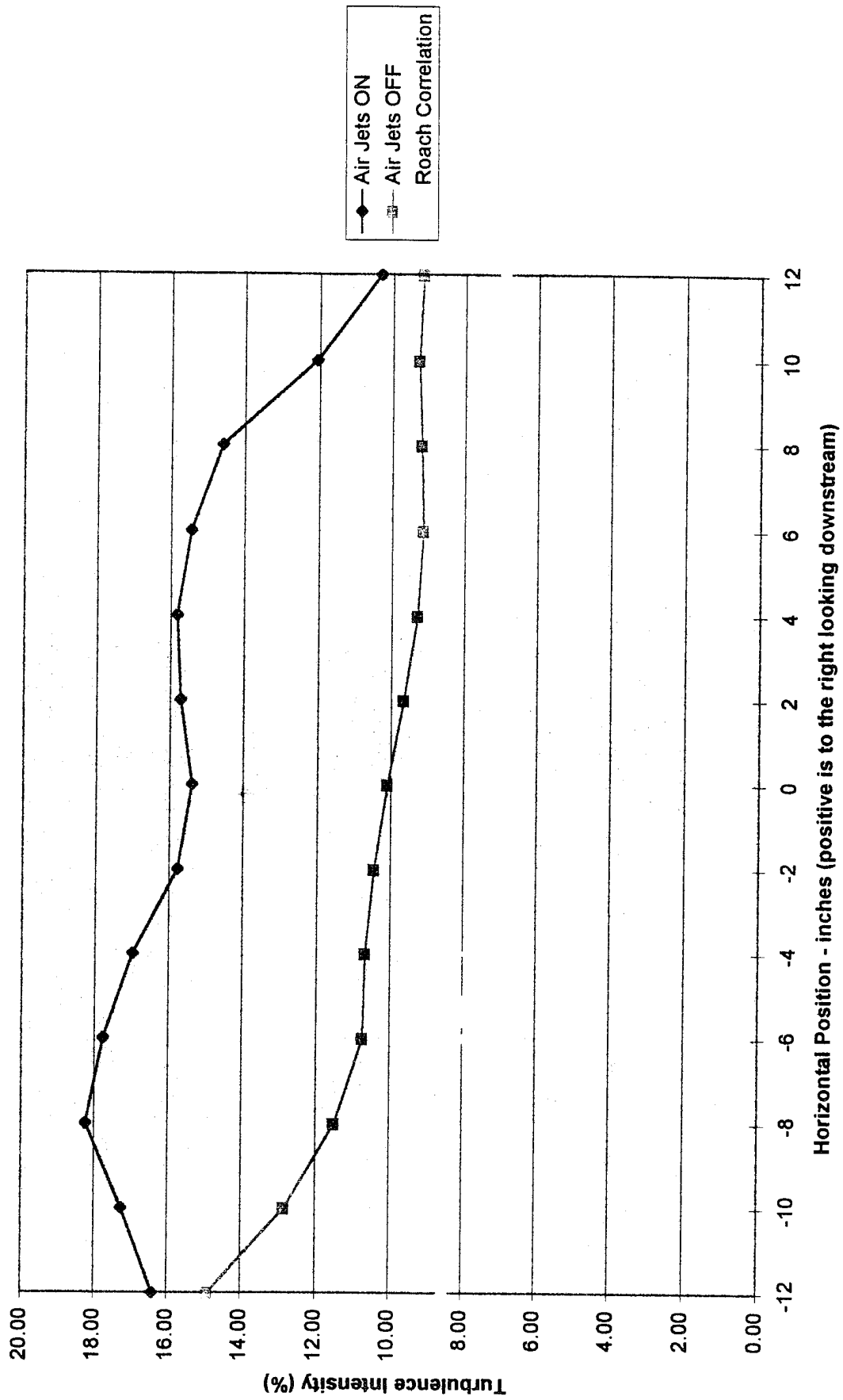


Chart5

# Effect of Air Jets on Turbulence Intensity - x=40"

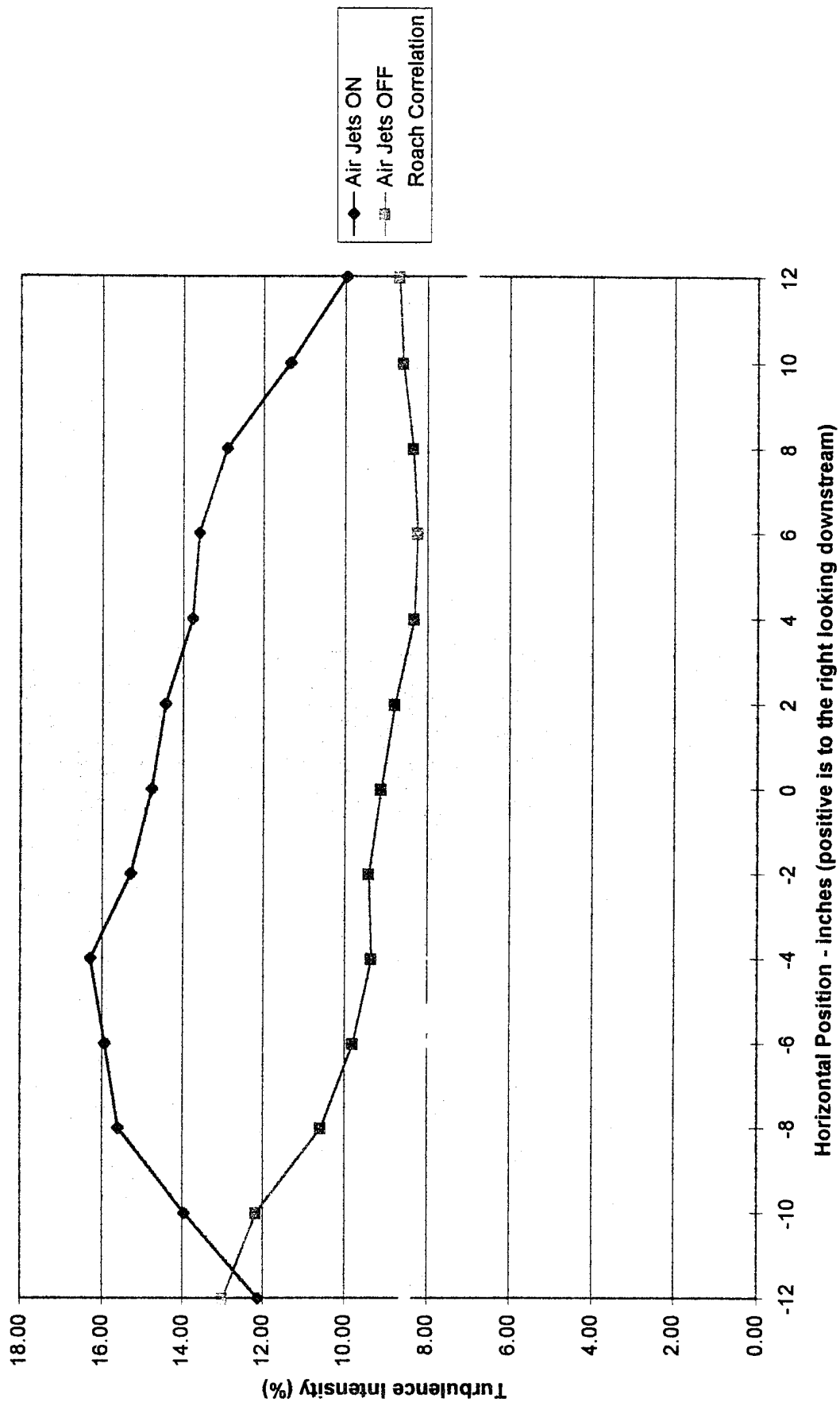


Chart5

Effect of Air Jets on Turbulence Intensity - x=40"

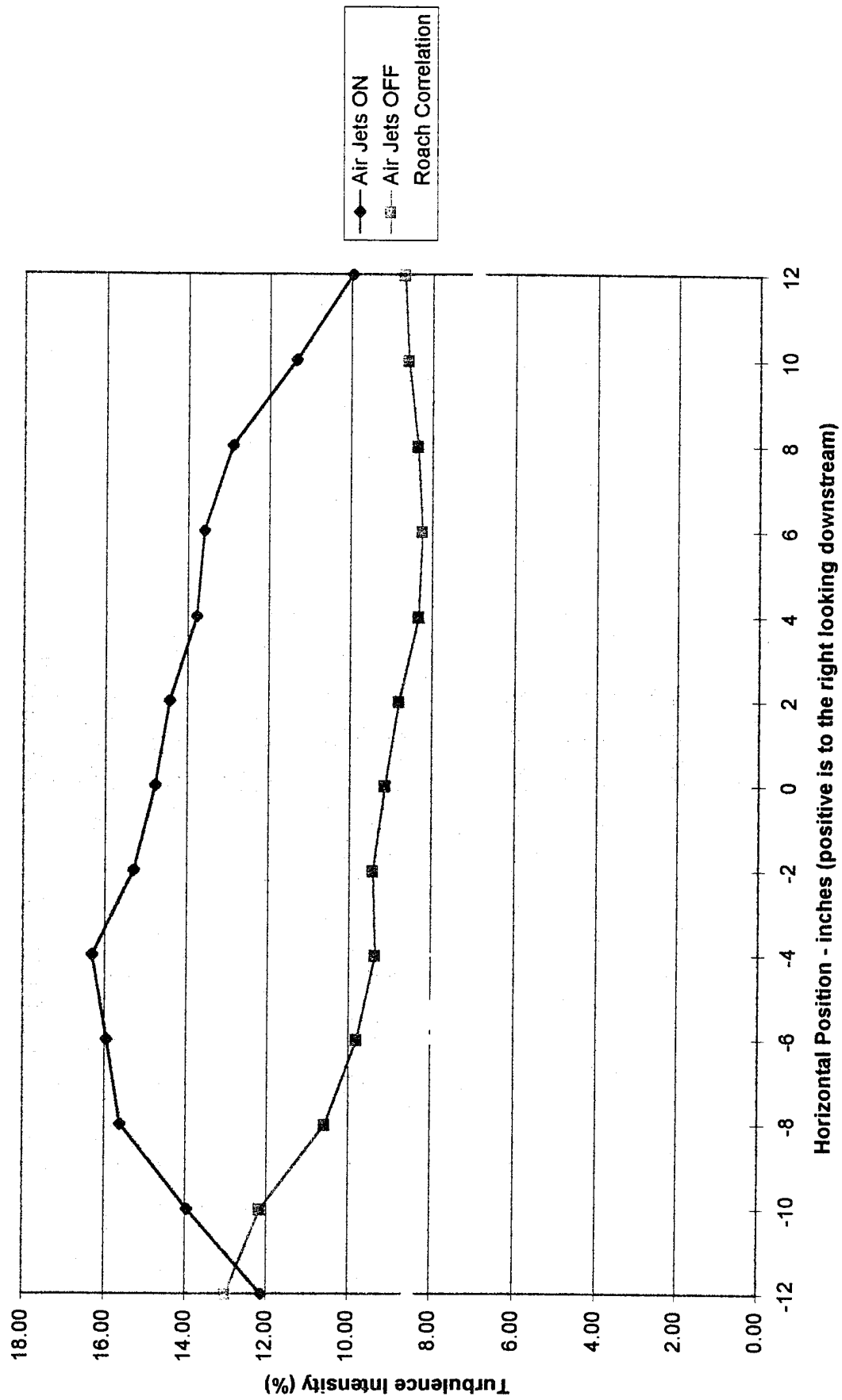
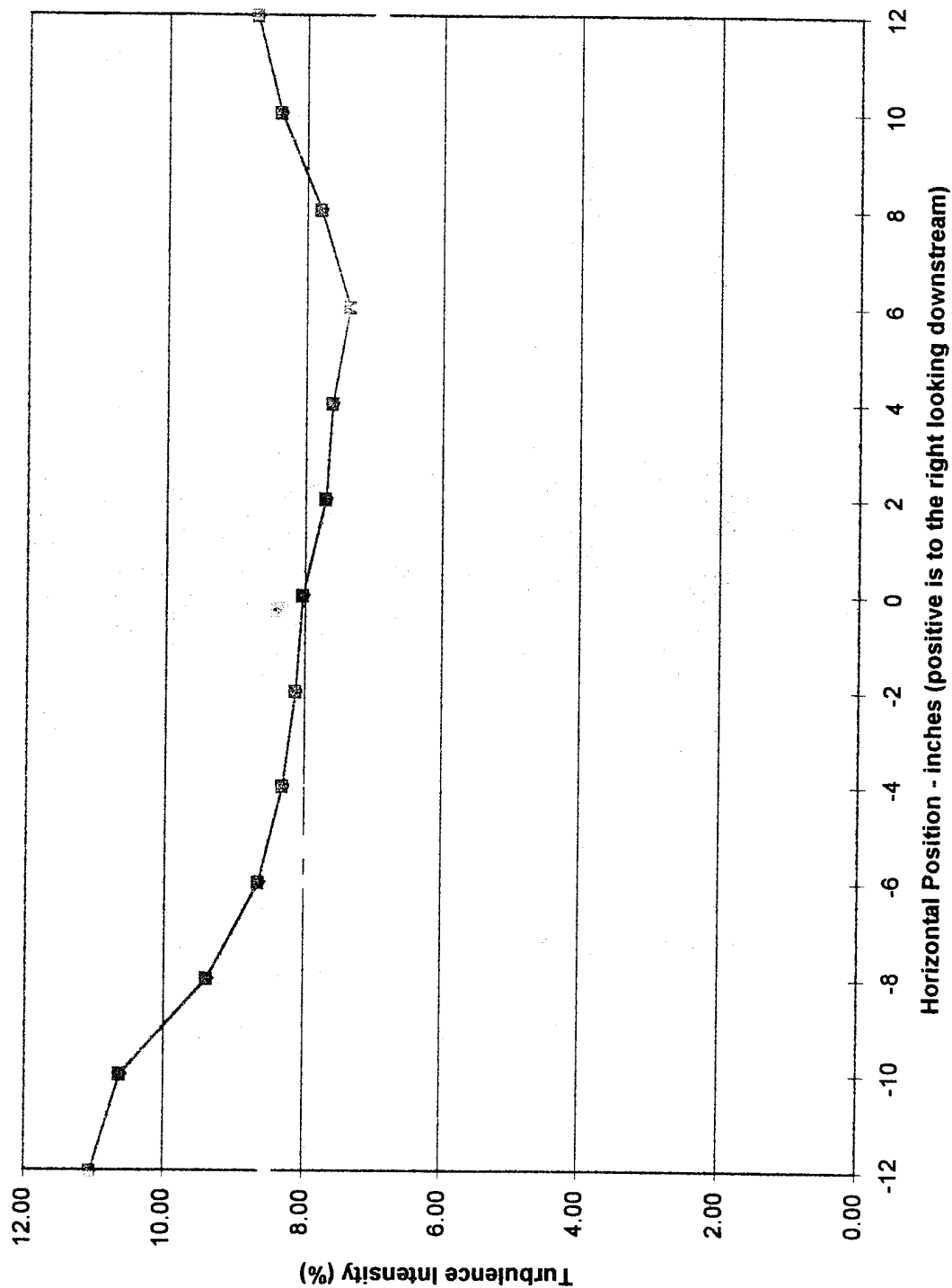


Chart5

# Effect of Air Jets on Turbulence Intensity - x=45.5"



◆ Air Jets ON (DATA UNAVAILABLE)  
 □ Air Jets OFF  
 --- Roach Correlation

Chart5

# Effect of Air Jets on Turbulence Intensity - x=52"

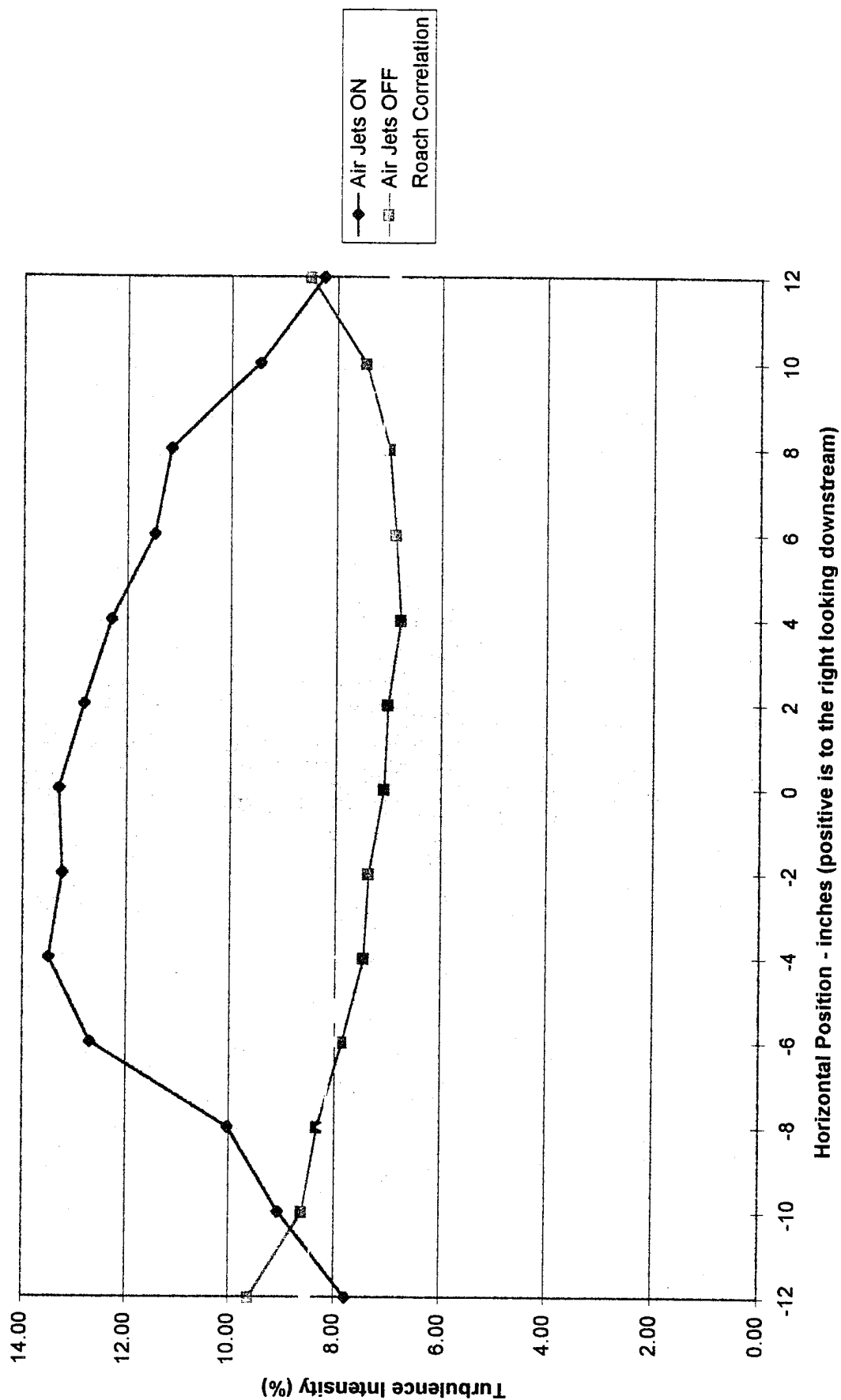


Chart5

# Effect of Air Jets on Turbulence Intensity - x=52"

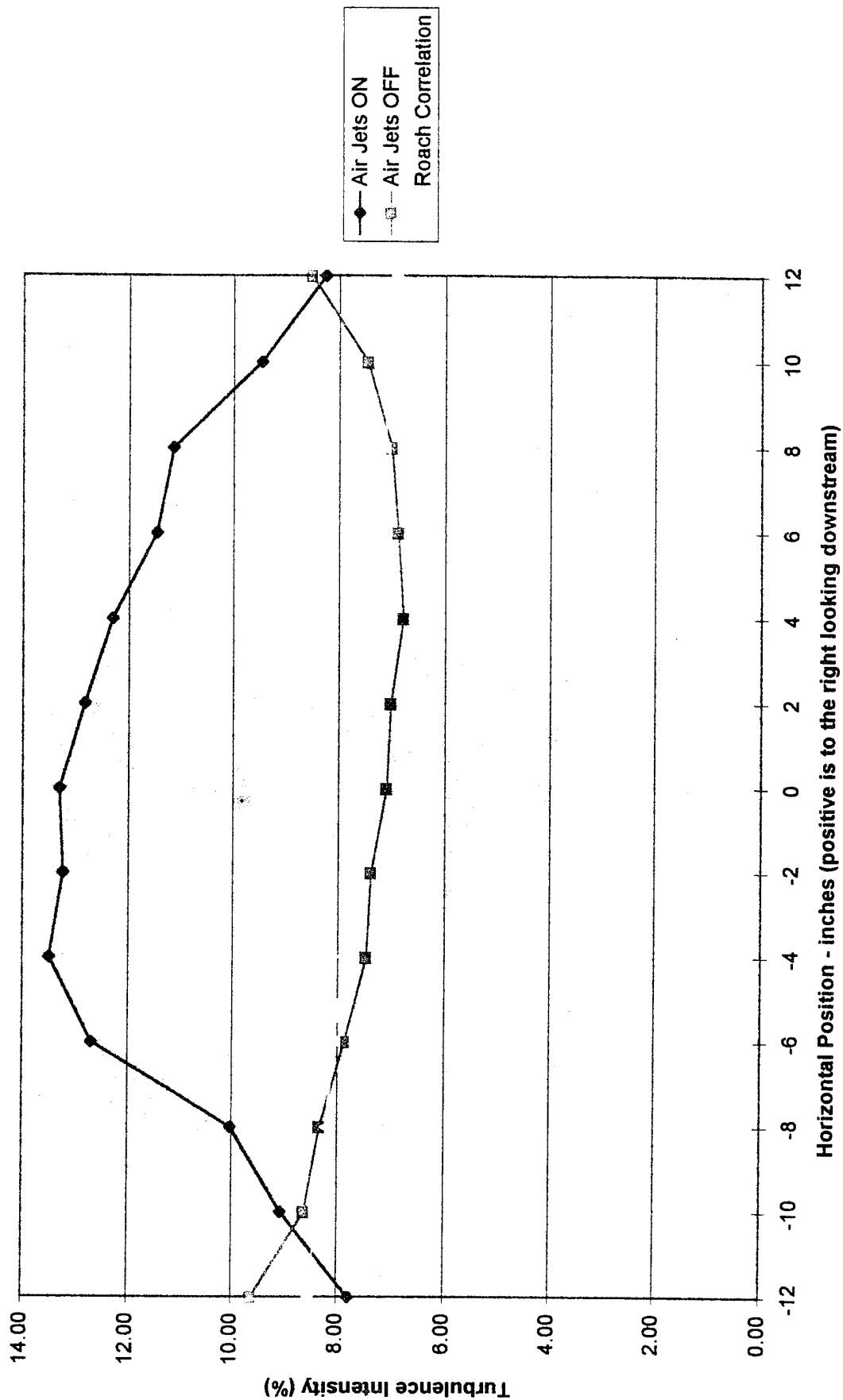




Chart5

Effect of Air Jets on Turbulence Intensity -  $x=67.5"$

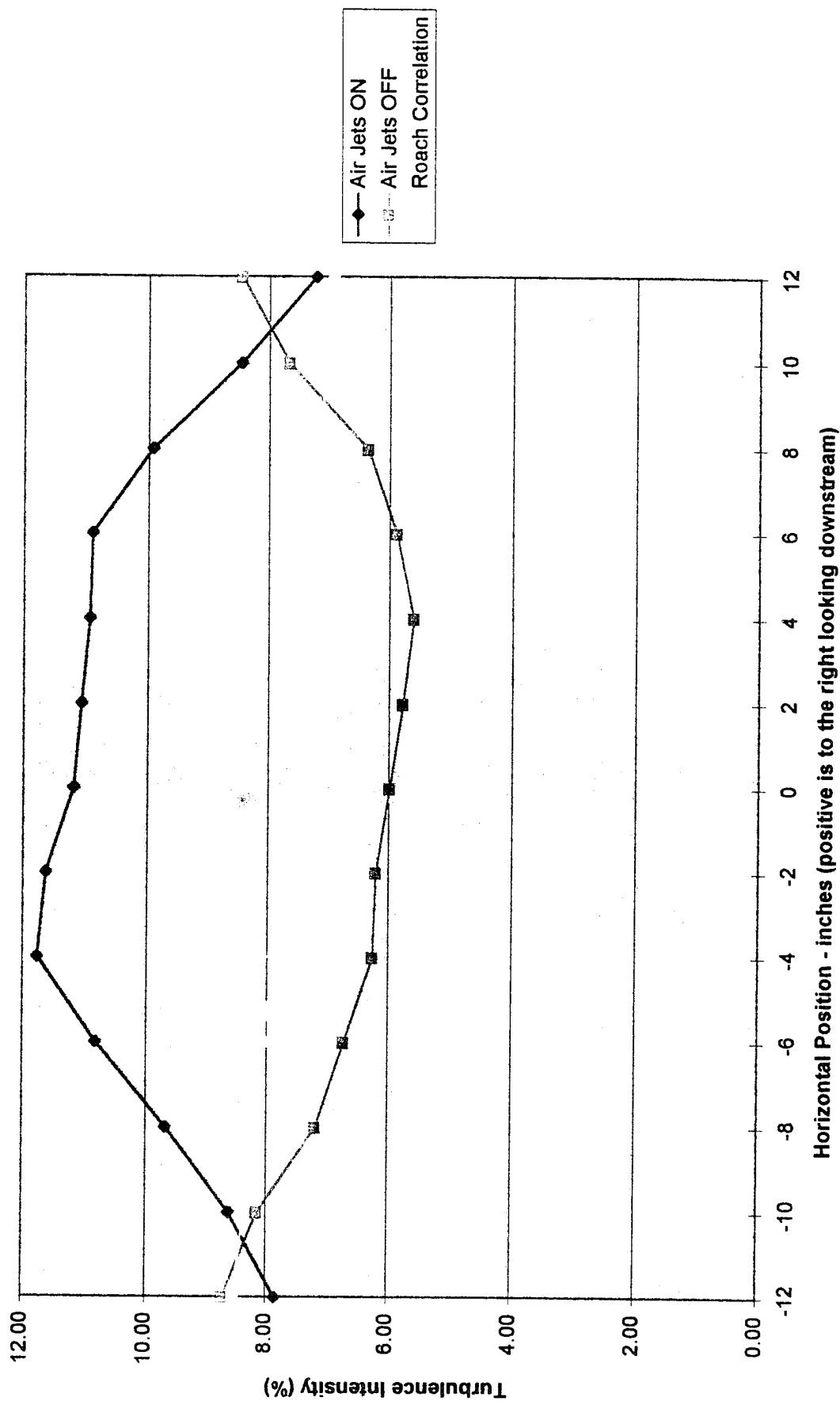
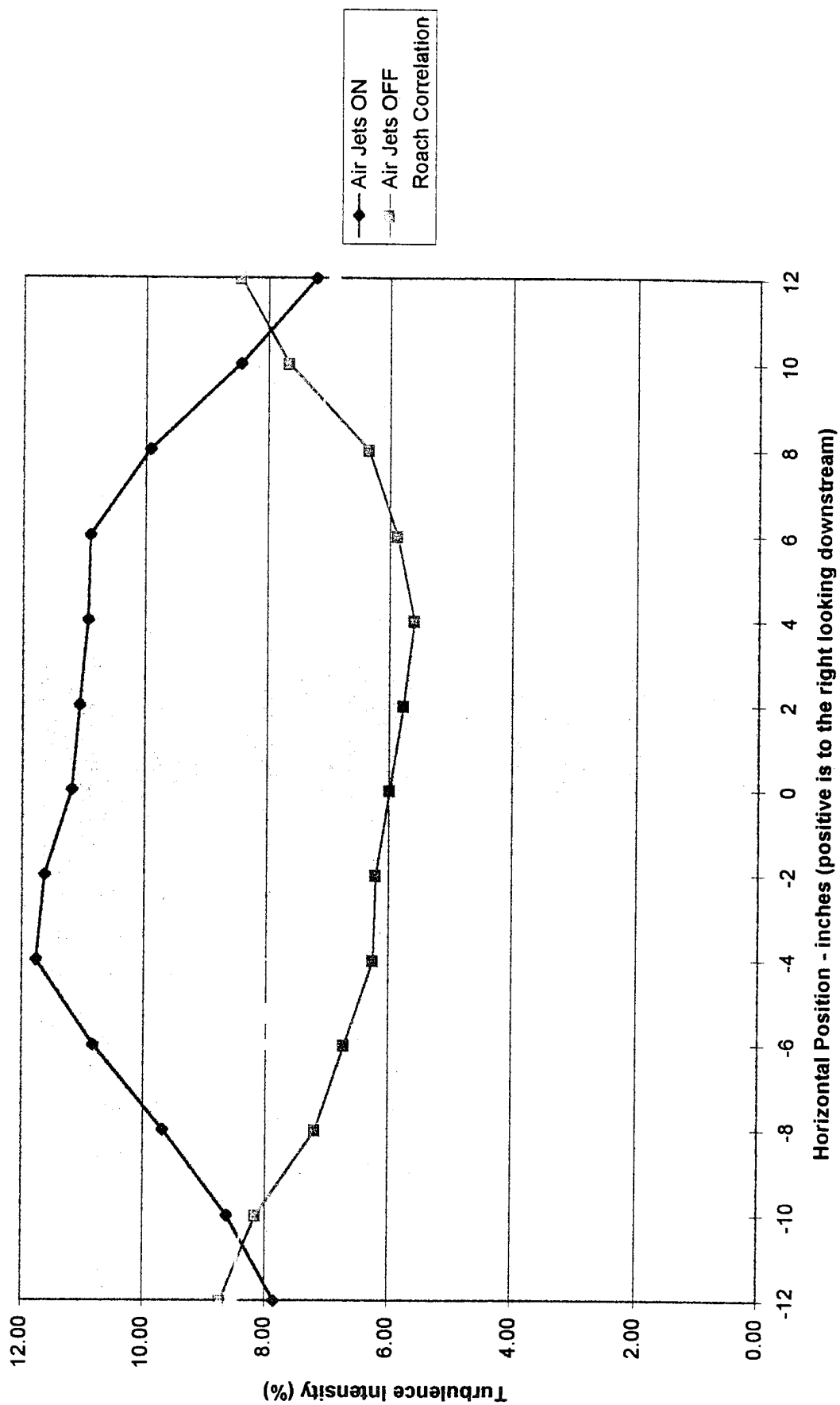


Chart5

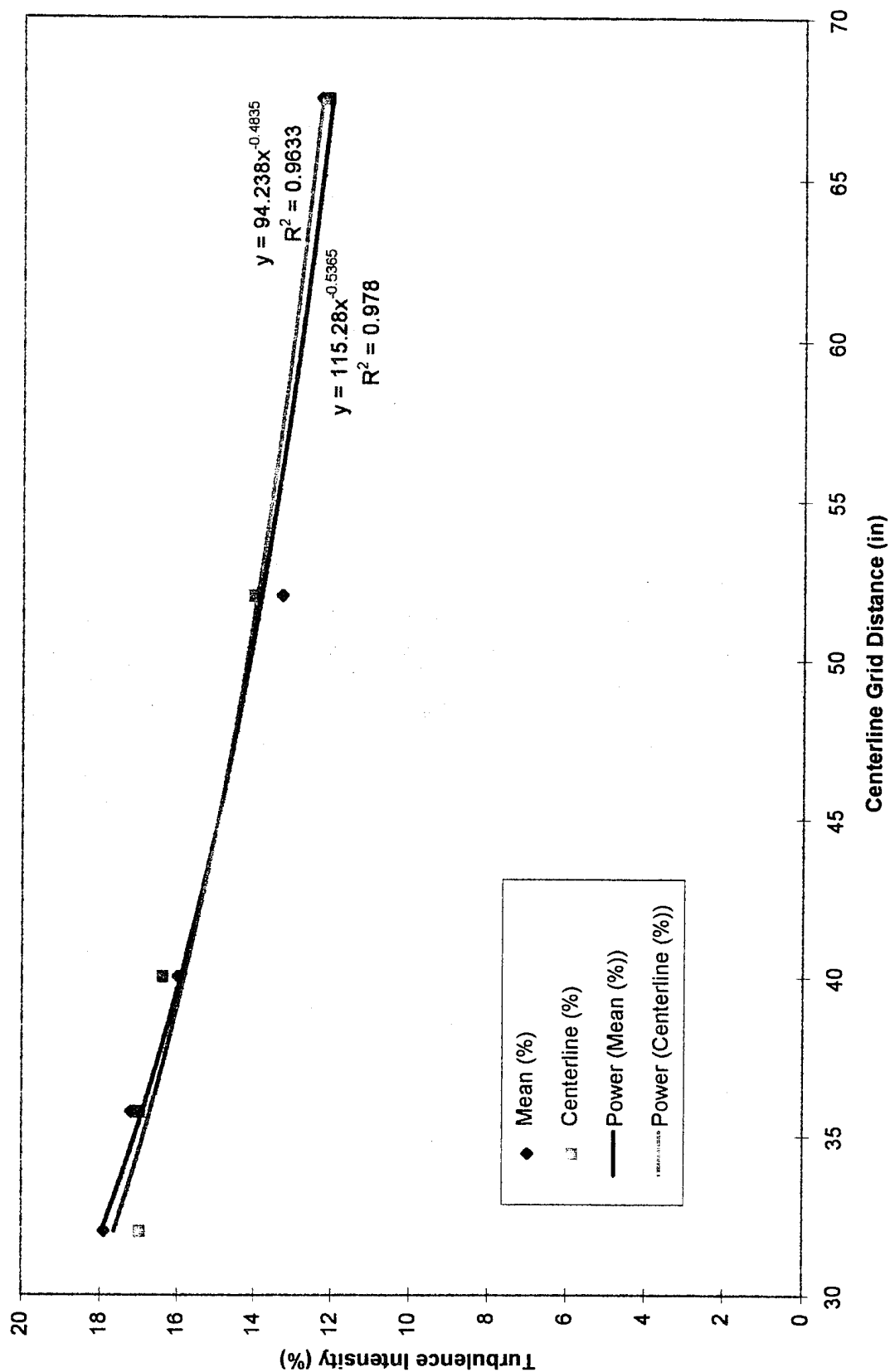
Effect of Air Jets on Turbulence Intensity - x=67.5"



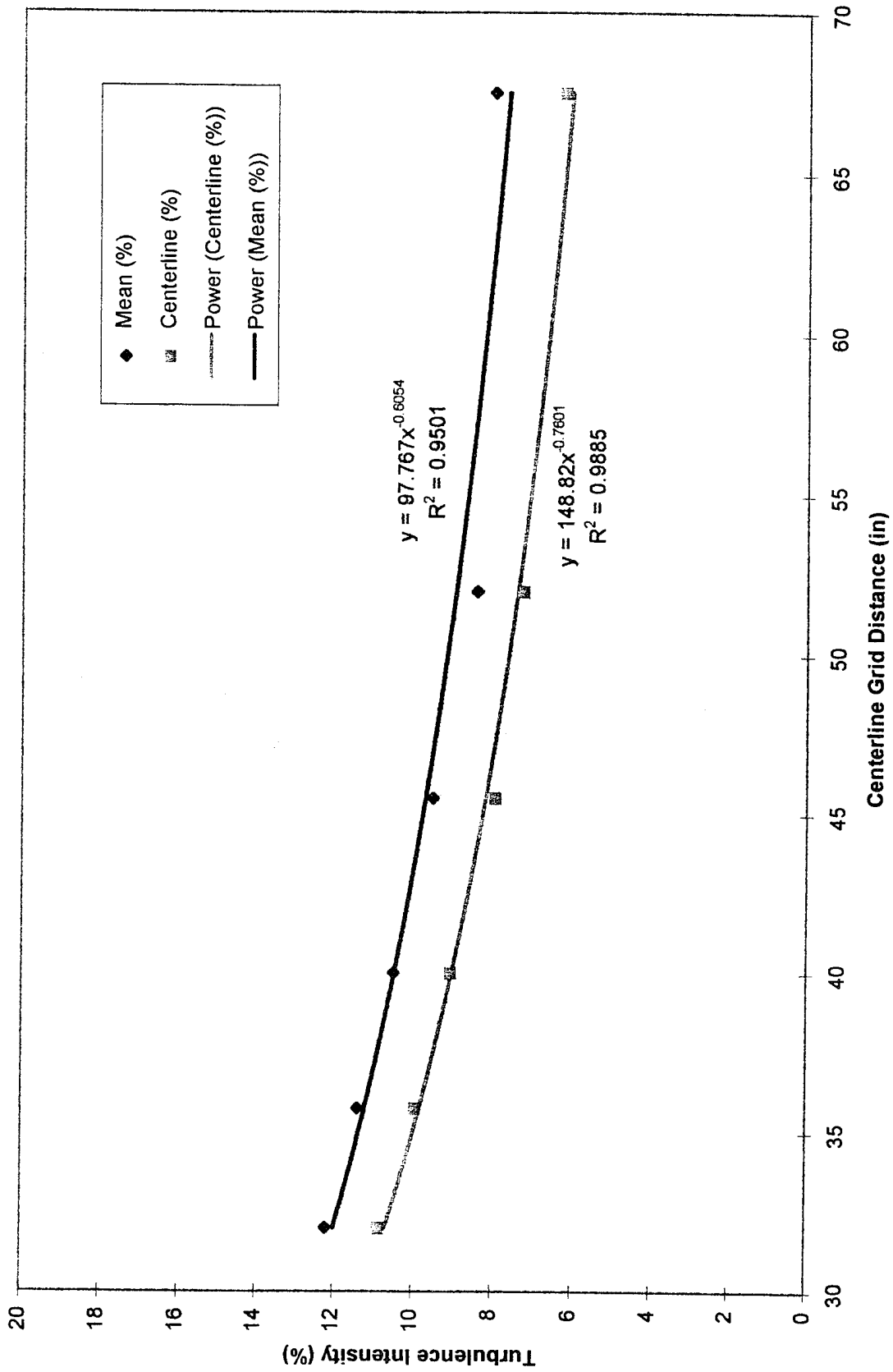
## **APPENDIX G:**

### **Turbulence Intensity Variation with Grid Distance (Decay Rates)**

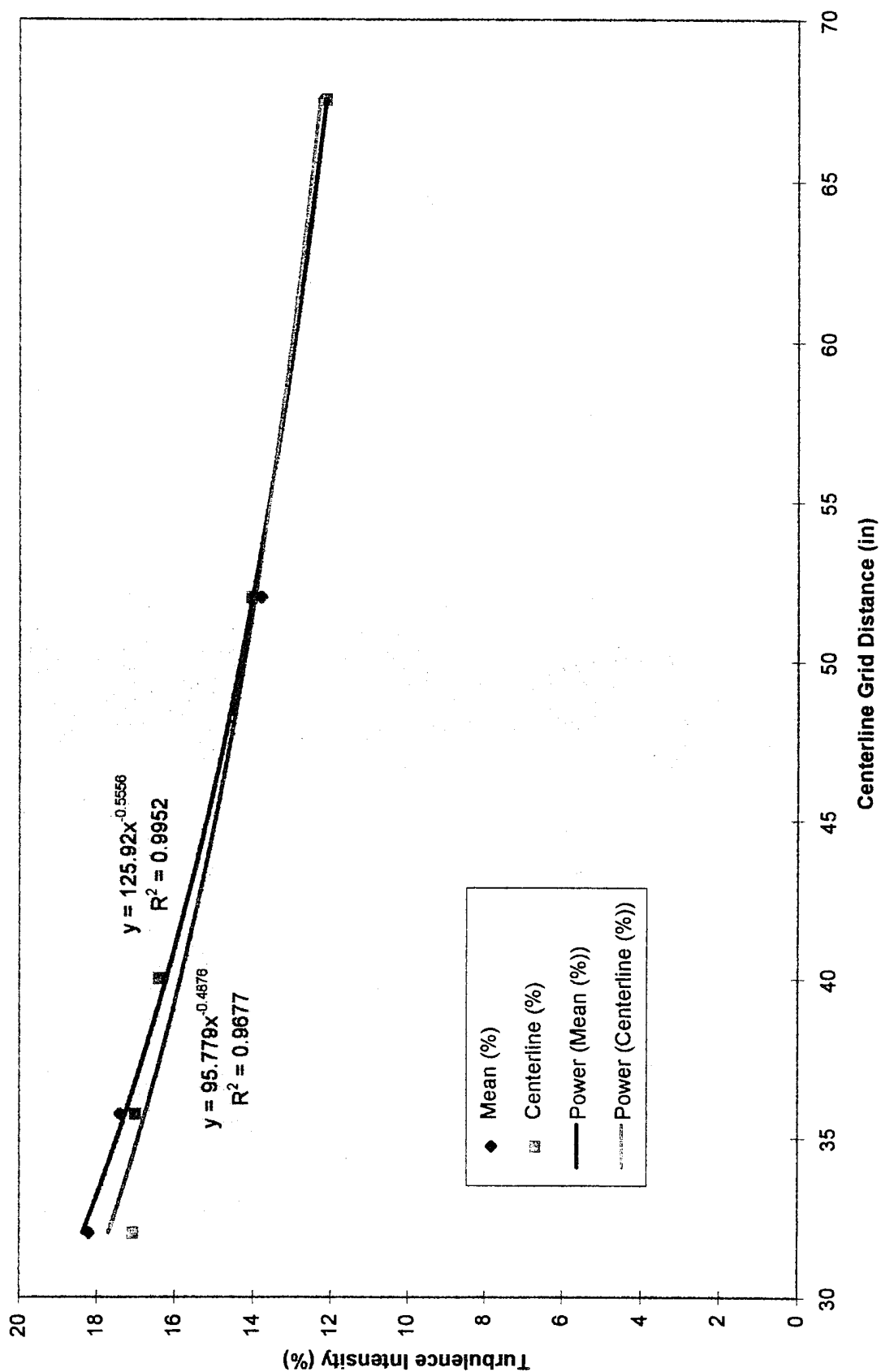
# Full Field Turbulence Intensities-Air Jets ON



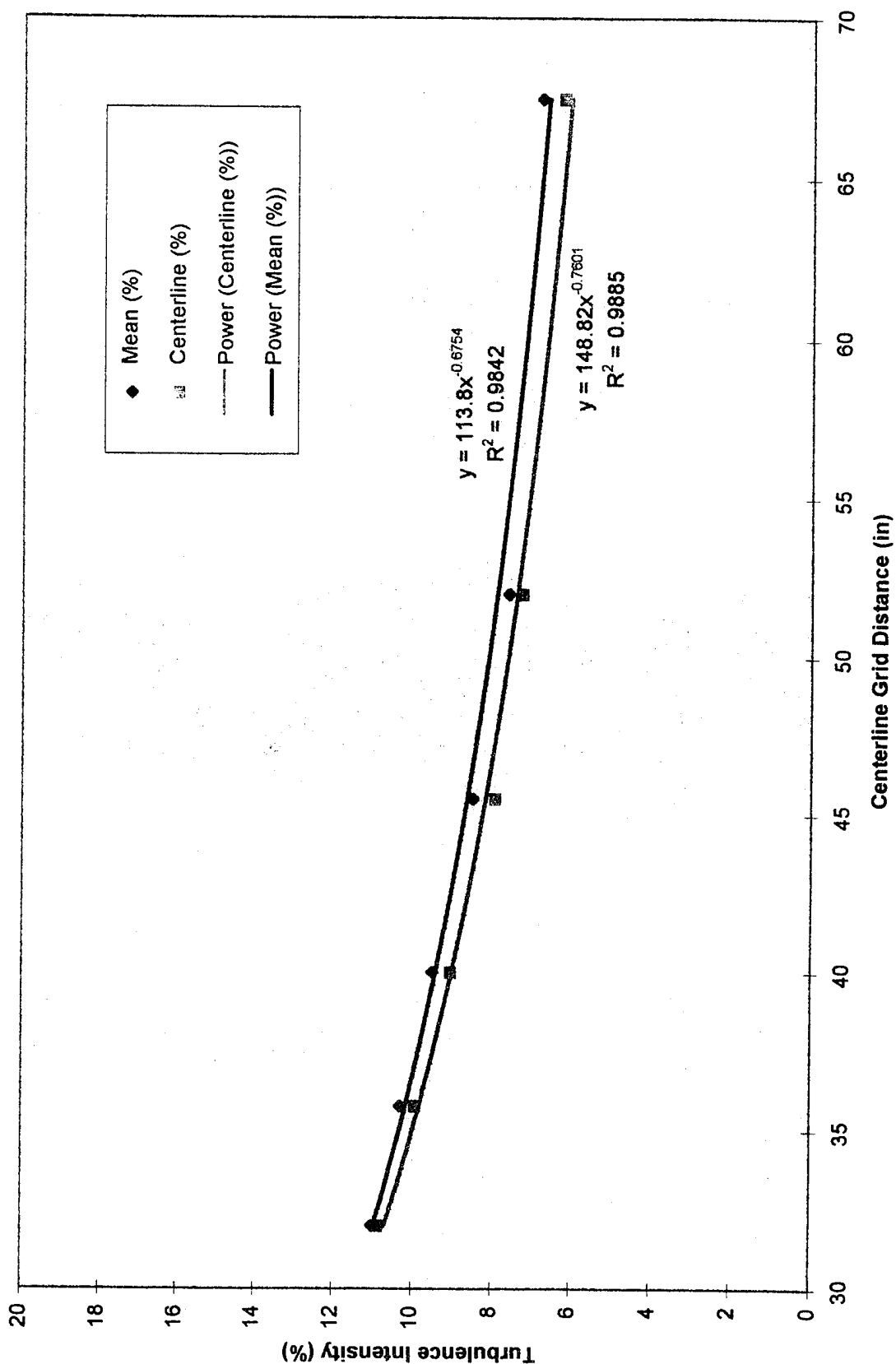
# Full Field Turbulence Intensities-Air Jets OFF



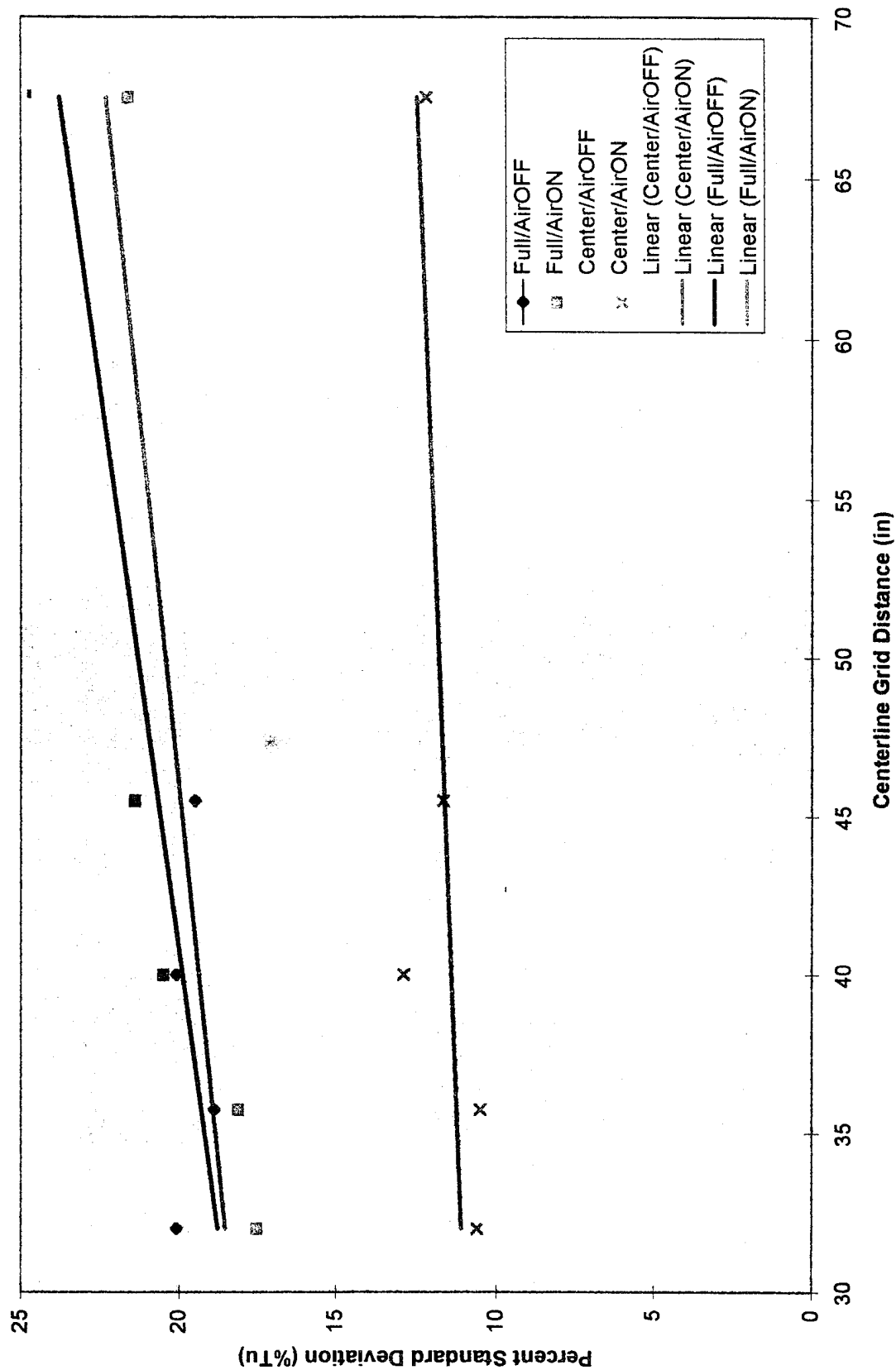
# Center Area Turbulence Intensities-Air Jets ON



## Center Area Turbulence Intensities-Air Jets OFF



# Standard Deviation in Turbulence Intensity vs Grid Distance

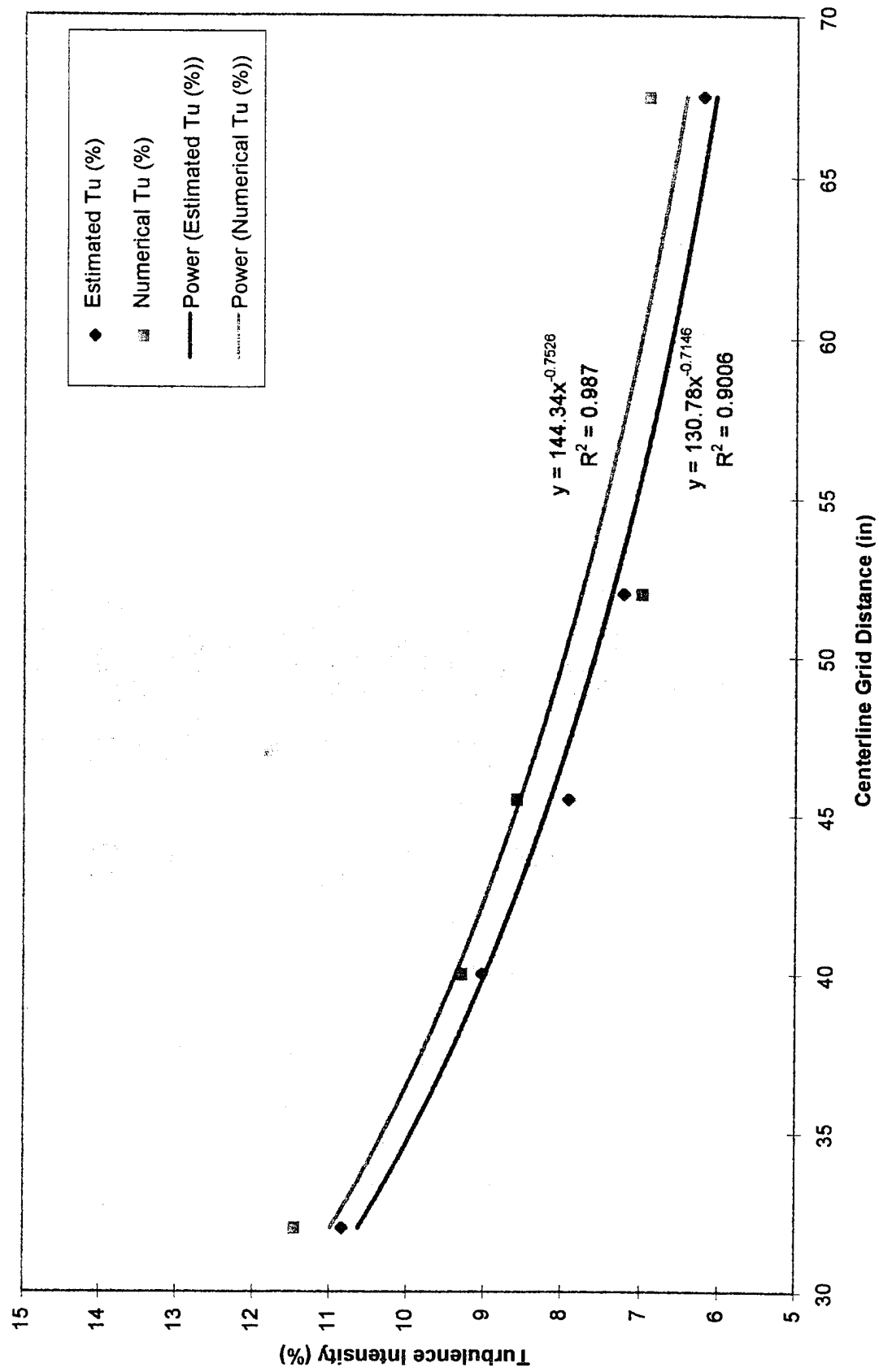




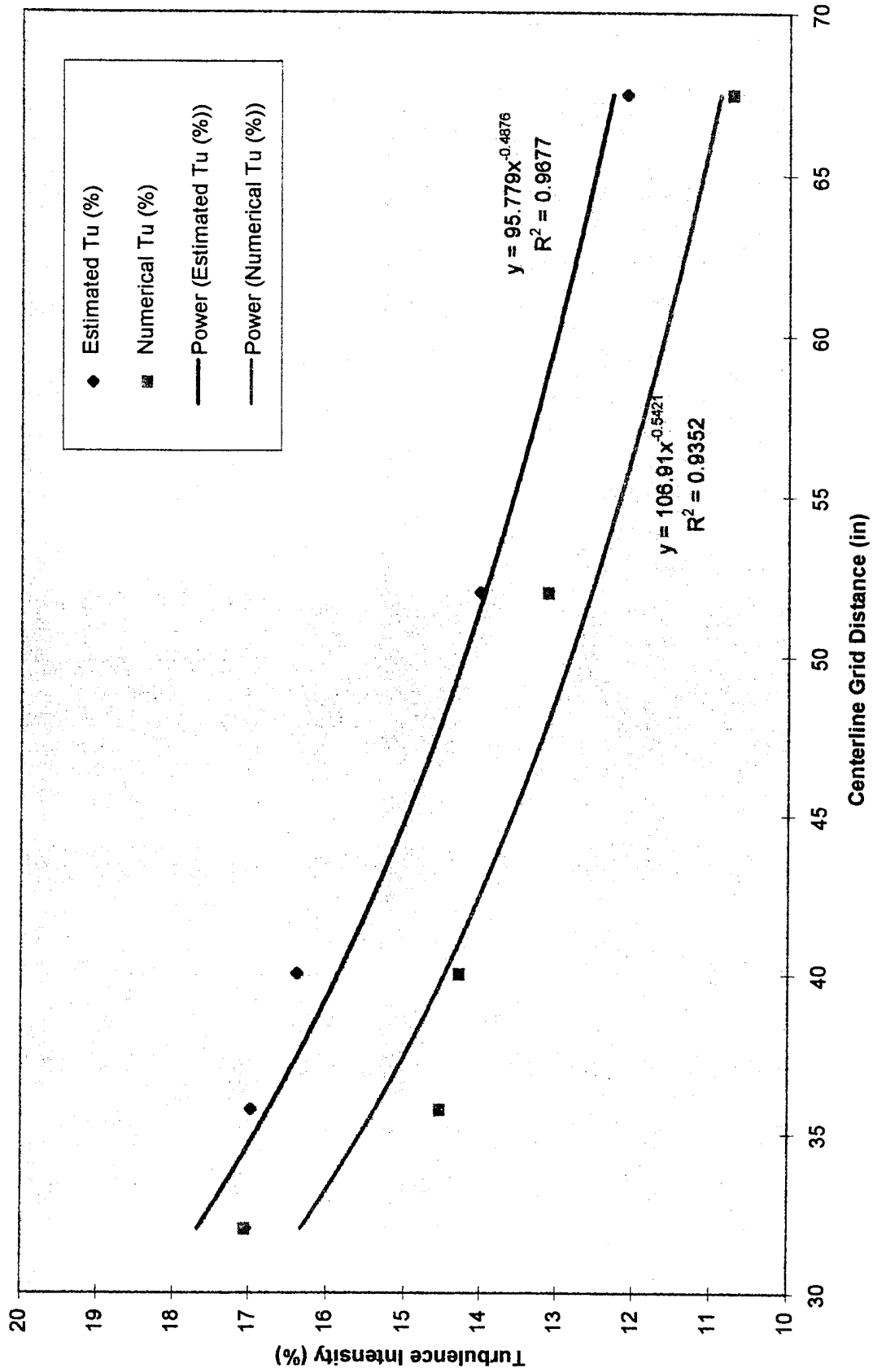
## APPENDIX H:

### Turbulence Intensity Calculation Method Comparison

# Turbulence Intensity Calculation Method Comparison - Air OFF



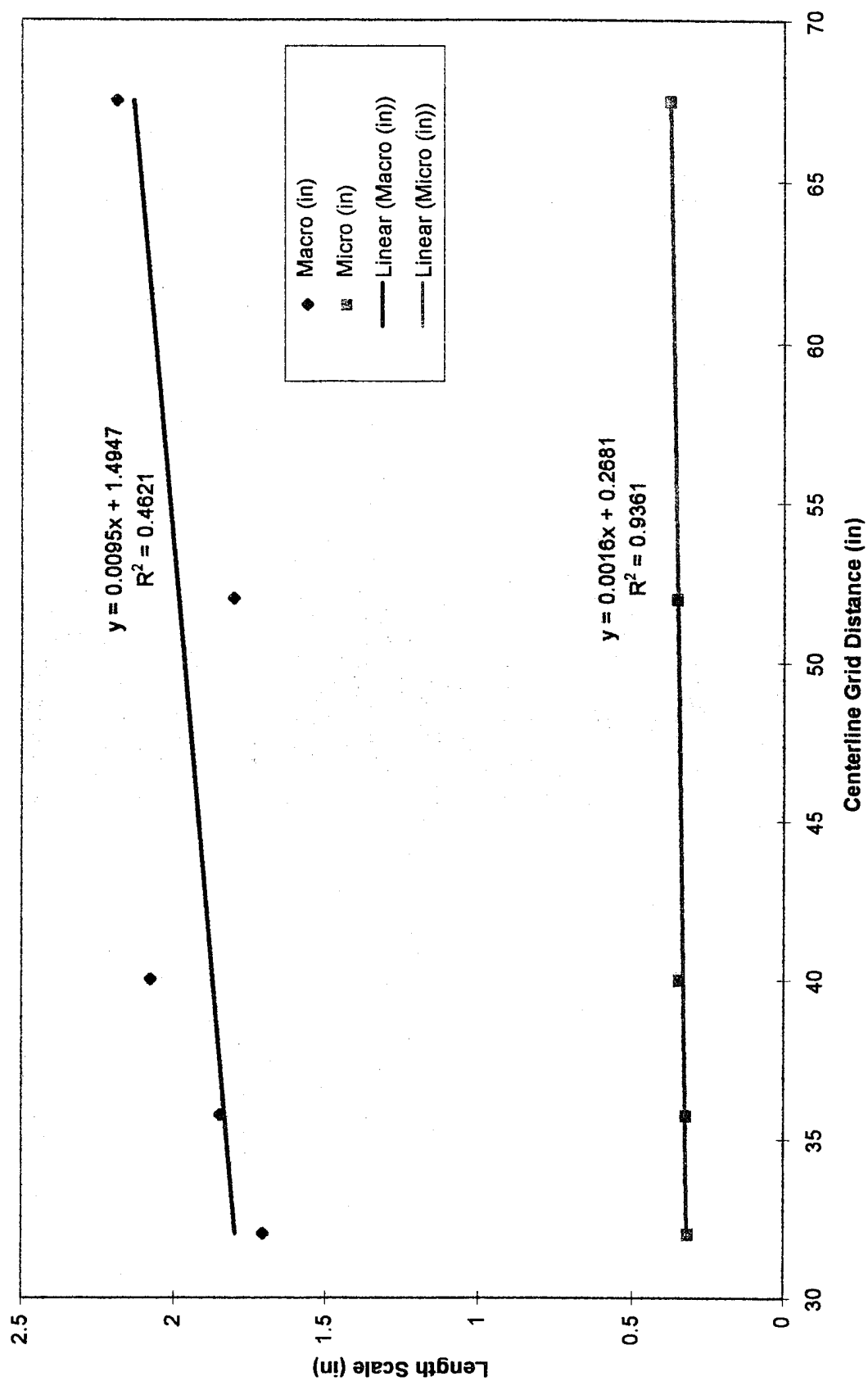
# Turbulence Intensity Calculation Method Comparison - Air ON



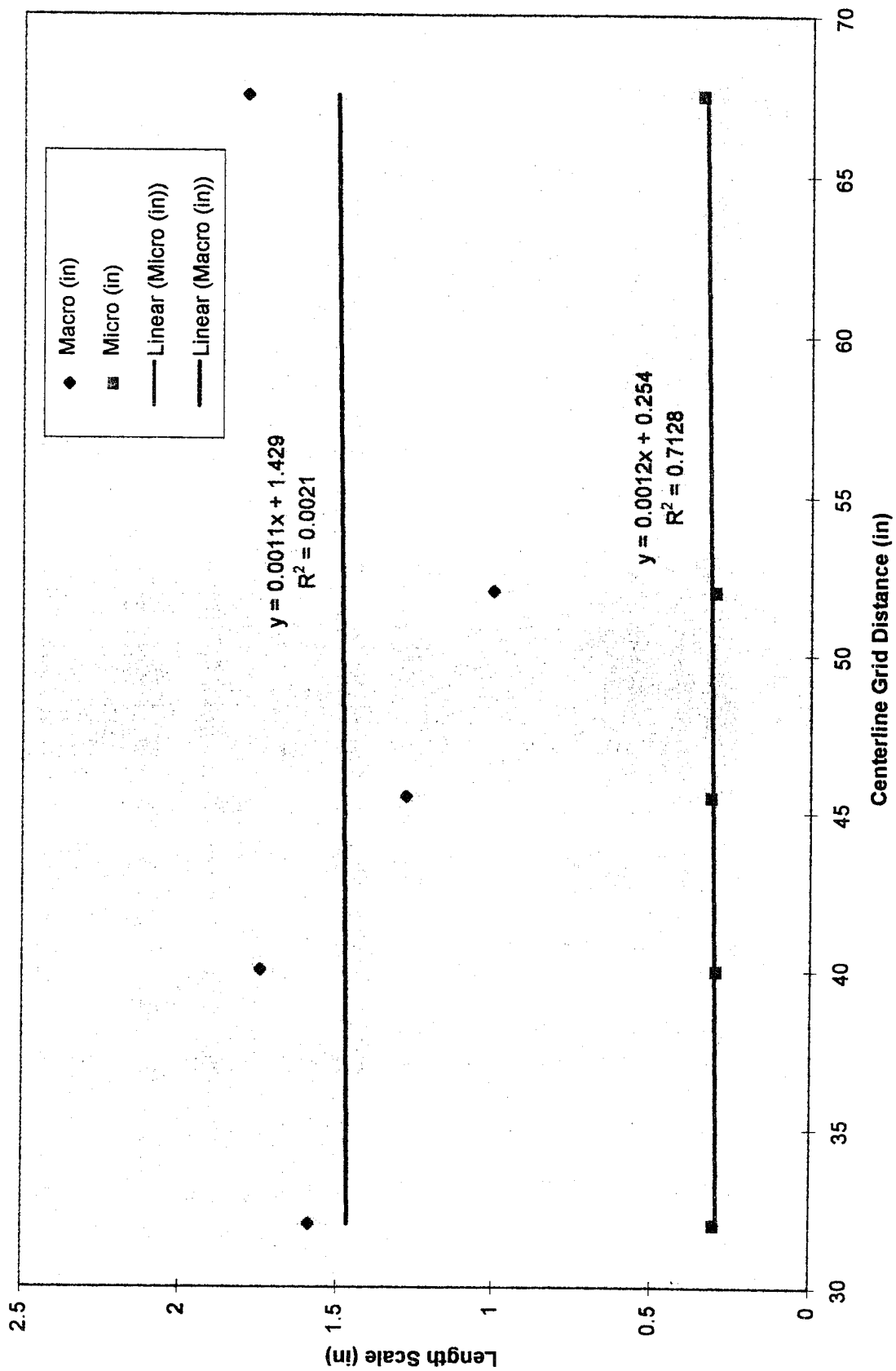
## **APPENDIX I:**

### Length Scale Variation with Distance

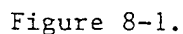
# Length Scale Variation with Distance - Air ON



# Length Scale Variation with Distance - Air OFF



The serial number is located on the rear label (see Figure 8-1) on both models.



Amplifier:

Amplifier Gain:  $>1 \times 10^6$

---

## 8. SPECIFICATIONS

### 8.1. Model 158

Number of Channels: 4 (allows control of up to 16 channels)

#### Test Signal Specifications - Model 158:

Type of Signal:	Square wave
Frequency Range:	0.3-30 kHz
Amplitude Range:	0-4.5 volts

#### Display Specifications - Model 158:

Number of digits:	4½
Resolution:	1 mV
Accuracy:	±2 digits
Sample Rate:	2.5 readings per second
Time Constant accuracy:	20%
Temperature Stability:	40 ppm typical

Output Impedance - Model 158: 100 ohm

Accessories:

1.8 m (6 ft) RS232 cable
1.8 m (6 ft) RG 58A/U output cable



## **APPENDIX J:**

### Sample Data Output and Reduction Spreadsheets

## SAMPLE DATA REDUCTION - ITERATED CORRELATION

## LENGTH SCALES FOR AIR JETS ON - POSITION 1

FACTOR FOR 7500 HZ  
CENTERLINE HOT WIRE

Lag	Time	R	Rbar*del t
1	0.000133	0.976	0.000127
2	0.000267	0.924	0.00012
3	0.0004	0.87	0.000113
4	0.000533	0.824	0.000108
5	0.000667	0.79	0.000104
6	0.0008	0.766	0.000101
7	0.000933	0.747	9.85E-05
8	0.001067	0.731	9.65E-05
9	0.0012	0.716	9.45E-05
10	0.001333	0.701	9.25E-05
11	0.001467	0.687	9.07E-05
12	0.0016	0.673	8.88E-05
13	0.001733	0.659	8.69E-05
14	0.001867	0.645	8.51E-05
15	0.002	0.632	8.34E-05
16	0.002133	0.619	8.17E-05
17	0.002267	0.607	8.01E-05
18	0.0024	0.595	7.87E-05
19	0.002533	0.585	7.73E-05
20	0.002667	0.575	0.000076
21	0.0028	0.565	7.46E-05
22	0.002933	0.554	7.31E-05
23	0.003067	0.542	7.13E-05
24	0.0032	0.528	6.95E-05
25	0.003333	0.515	6.78E-05
26	0.003467	0.502	6.62E-05
27	0.0036	0.491	6.49E-05
28	0.003733	0.482	6.37E-05
29	0.003867	0.473	6.25E-05
30	0.004	0.465	6.14E-05
31	0.004133	0.456	6.02E-05
32	0.004267	0.447	5.89E-05
33	0.0044	0.437	5.76E-05
34	0.004533	0.427	5.62E-05
35	0.004667	0.416	5.48E-05
36	0.0048	0.406	5.34E-05
37	0.004933	0.395	5.19E-05
38	0.005067	0.384	5.05E-05
39	0.0052	0.374	4.92E-05
40	0.005333	0.364	0.000048
41	0.005467	0.356	4.69E-05
42	0.0056	0.348	4.58E-05
43	0.005733	0.339	4.47E-05
44	0.005867	0.331	4.35E-05
45	0.006	0.322	4.23E-05
46	0.006133	0.313	4.12E-05
47	0.006267	0.305	4.03E-05
48	0.0064	0.299	3.96E-05
49	0.006533	0.295	3.93E-05

50	0.006667	0.294	3.91E-05
51	0.0068	0.293	3.89E-05
52	0.006933	0.291	3.85E-05
53	0.007067	0.287	3.81E-05
54	0.0072	0.284	3.76E-05
55	0.007333	0.28	3.71E-05
56	0.007467	0.276	3.65E-05
57	0.0076	0.272	3.59E-05
58	0.007733	0.267	3.53E-05
59	0.007867	0.262	3.45E-05
60	0.008	0.256	3.37E-05
61	0.008133	0.25	0.000033
62	0.008267	0.245	3.22E-05
63	0.0084	0.238	3.13E-05
64	0.008533	0.231	3.02E-05
65	0.008667	0.222	0.000029
66	0.0088	0.213	2.78E-05
67	0.008933	0.204	2.67E-05
68	0.009067	0.196	2.57E-05
69	0.0092	0.189	2.48E-05
70	0.009333	0.183	0.000024
71	0.009467	0.177	2.31E-05
72	0.0096	0.17	2.22E-05
73	0.009733	0.163	2.13E-05
74	0.009867	0.157	2.05E-05
75	0.01	0.151	1.98E-05
76	0.010133	0.146	1.91E-05
77	0.010267	0.141	1.85E-05
78	0.0104	0.137	1.79E-05
79	0.010533	0.132	1.72E-05
80	0.010667	0.126	1.64E-05
81	0.0108	0.12	1.56E-05
82	0.010933	0.114	1.48E-05
83	0.011067	0.108	1.42E-05
84	0.0112	0.105	1.38E-05
85	0.011333	0.102	1.35E-05
86	0.011467	0.1	1.33E-05
87	0.0116	0.099	1.31E-05
88	0.011733	0.097	1.27E-05
89	0.011867	0.094	1.24E-05
90	0.012	0.092	1.21E-05
91	0.012133	0.09	1.19E-05
92	0.012267	0.088	1.15E-05
93	0.0124	0.084	1.09E-05
94	0.012533	0.08	1.03E-05
95	0.012667	0.075	9.67E-06
96	0.0128	0.07	9.13E-06
97	0.012933	0.067	8.73E-06
98	0.013067	0.064	8.33E-06
99	0.0132	0.061	7.93E-06
100	0.013333	0.058	7.47E-06

101	0.013467	0.054	6.87E-06
102	0.0136	0.049	6.13E-06
103	0.013733	0.043	5.4E-06
104	0.013867	0.038	4.8E-06
105	0.014	0.034	4.4E-06
106	0.014133	0.032	4.2E-06
107	0.014267	0.031	4.07E-06
108	0.0144	0.03	3.87E-06
109	0.014533	0.028	3.6E-06
110	0.014667	0.026	3.2E-06
111	0.0148	0.022	2.73E-06
112	0.014933	0.019	2.27E-06
113	0.015067	0.015	1.8E-06
114	0.0152	0.012	1.47E-06
115	0.015333	0.01	1.33E-06
116	0.015467	0.01	1.33E-06
117	0.0156	0.01	1.27E-06
118	0.015733	0.009	1.07E-06
119	0.015867	0.007	7.33E-07
120	0.016	0.004	

sum = 0.00466

LENGTH SCALES

macro (m) macro (in)  
0.043348 1.706624

Vmean = 9.303  
Std Dev = 1.586

micro (m) micro (in)  
0.008007 0.315226

Tu = 0.170483

101	0.013467	0.054	6.87E-06
102	0.0136	0.049	6.13E-06
103	0.013733	0.043	5.4E-06
104	0.013867	0.038	4.8E-06
105	0.014	0.034	4.4E-06
106	0.014133	0.032	4.2E-06
107	0.014267	0.031	4.07E-06
108	0.0144	0.03	3.87E-06
109	0.014533	0.028	3.6E-06
110	0.014667	0.026	3.2E-06
111	0.0148	0.022	2.73E-06
112	0.014933	0.019	2.27E-06
113	0.015067	0.015	1.8E-06
114	0.0152	0.012	1.47E-06
115	0.015333	0.01	1.33E-06
116	0.015467	0.01	1.33E-06
117	0.0156	0.01	1.27E-06
118	0.015733	0.009	1.07E-06
119	0.015867	0.007	7.33E-07
120	0.016	0.004	

sum = 0.00466

## LENGTH SCALES

macro (m) macro (in)  
0.043348 1.706624

Vmean = 9.303  
Std Dev = 1.586

micro (m) micro (in)  
0.008007 0.315226

Tu = 0.170483

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